

VOL.107 NO.TC1. APRIL 1981

# JOURNAL OF THE TECHNICAL COUNCILS OF ASCE

PROCEEDINGS OF  
THE AMERICAN SOCIETY  
OF CIVIL ENGINEERS



CODES AND STANDARDS  
COLD REGIONS ENGINEERING  
COMPUTER PRACTICES  
LIFELINE EARTHQUAKE ENGINEERING  
RESEARCH



VOL.107 NO.TC1. APRIL 1981

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LIFELINE EARTHQUAKE ENGINEERING  
RESEARCH

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The most recent issues of this journal were published in November 1978, April 1979, December 1979, and August 1980.

The Society is not responsible for any statement made or opinion expressed in its publications.

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# INFORMATION RETRIEVAL

The key words, abstract, and reference "cards" for each article in this Journal represent part of the ASCE participation in the EJC information retrieval plan. The retrieval data are placed herein so that each can be cut out, placed on a 3 x 5 card and given an accession number for the user's file. The accession number is then entered on key word cards so that the user can subsequently match key words to choose the articles he wishes. Details of this program were given in an August, 1962 article in CIVIL ENGINEERING, reprints of which are available on request to ASCE headquarters.

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\*Discussion period closed for this paper. Any other discussion received during this discussion period will be published in subsequent Journals.



## 16159 SEISMIC DESIGN OF PUMPING PLANTS

**KEY WORDS:** Earthquake damage; Earthquake engineering; Earthquake resistant structures; Municipal wastes; Municipal water; **Pumping plants;** Seismic design; Sewage treatment plants; **Water supply;** Water treatment plants

**ABSTRACT:** Pumping plants that serve water supply and sewage systems are important lifeline facilities, and they should remain in operation or be readily repairable following earthquake damage. Water distribution pumping is necessary to maintain sufficient storage to fight fires and to provide minimum potable water and other critical disaster needs. When sewage pumping stations are down, the results can be serious health hazards or environmental damage from sewage spillage or treatment plant bypasses. Typical damage to equipment and piping (similar to that found in pumping plants resulting from the 1971 San Fernando Earthquake) is unidentified. Modern engineering practices for the seismic design of water supply and sewage pumping plants are reviewed, as are procedures used at the writer's utility district and a list of suggested seismic design considerations.

**REFERENCE:** Anton, Walter F., "Seismic Design of Pumping Plants," *Journal of the Technical Councils*, ASCE, Vol. 107, No. TC1, **Proc. Paper 16159**, April, 1981, pp. 1-12

## 16160 COST-PLUS CONTRACTOR SELECTION

**KEY WORDS:** Contract administration; Contracted services; **Contracts;** **Cost plus contracts;** Decision making; **Economic analysis;** **Nuclear power plants;** Utility theory; Value analysis

**ABSTRACT:** A method for quantifying and measuring the effectiveness of contractors competing for a cost-plus contract has been developed. The methodology is demonstrated within the context of a \$40,000,000 cost-plus incentive fee contract for electrical work on a nuclear power station. Four candidate contractors are evaluated and ranked using a multicriterion decision model. Comparisons are made between the decision model rankings and those arrived at by more traditional means. The procedure demonstrates the viability of a quantitative approach to a heretofore qualitative problem. Although not accomplished here, the procedure may be adapted to the selection of fixed price contractors as well.

**REFERENCE:** Diekmann, James E., "Cost-Plus Contractor Selection: A Case Study," *Journal of the Technical Councils*, ASCE, Vol. 107, No. TC1, **Proc. Paper 16160**, April, 1981, pp. 13-25

## 16162 LNG TERMINAL DESIGN FOR CALIFORNIA

**KEY WORDS:** California; Docks; Dynamic stability; **Earthquakes;** Energy; **Liquefied natural gas;** Pipelines; **Pipeline terminals;** **Safety standards;** Specifications; **Tanks (containers);** **Terminal facilities**

**ABSTRACT:** An LNG receiving terminal is under design for the coast of California. This is the first terminal to be designed under recently established California LNG safety standards. These standards are reviewed as they relate to earthquake engineering, and they are compared with other existing criteria. Seismic criteria, special studies and major earthquake-related design features incorporated to comply with these standards are explored, and the design impact on LNG storage tanks, marine facilities and other major structures is examined. The lifeline earthquake engineering aspects of the project (reliability and safety) coupled with the seismicity of the site (0.7g SSE spectra) result in design requirements more conservative than those specified for most nuclear power plants. The project criteria are believed to incorporate the most current philosophy with regard to safety critical, non-nuclear lifeline facilities.

**REFERENCE:** Anderson, Thomas L., and Bachman, Robert E., "LNG Terminal Design for California," *Journal of the Technical Councils*, ASCE, Vol. 107, No. TC1, **Proc. Paper 16162**, April, 1981, pp. 27-39

## 16167 ANALYSIS OF WATER RESOURCE SYSTEMS

**KEY WORDS:** Computer analysis; Computerized simulation; Data processing; Hydraulics; Hydrology; Mathematical models; Simulation; Systems analysis; Water resources

**ABSTRACT:** Computer simulation models of large or geometrically complex systems, or both, are found in hydraulic, hydrology and water resources engineering; they require automated interactive mesh generators and data processors for efficient project implementation. A preprocessor is reviewed that consists of data processors, mesh generators, and graphics routines; it is capable of: (1) Selecting the most suitable numerical method for solving water resources and related problems; (2) storing the system's boundaries and generating appropriate meshes; and (3) displaying intermediates as well as final results of the computer simulation model in graphical form. This interactive preprocessor is a flexible, portable and easy-to-use software package which facilitates the research and development work of scientists and engineers.

**REFERENCE:** Kleinstreuer, Clement, "Computer-Aided Analysis of Water Resource Systems," *Journal of the Technical Councils*, ASCE, Vol. 107, No. TC1, **Proc. Paper 16167**, April, 1981, pp. 41-53

## 16166 OBSERVATION OF A FATIGUE DAMAGED BRIDGE

**KEY WORDS:** Analysis; Bridges; Bridges (highway); Cracking; Crack propagation; Fatigue (materials); Fatigue tests; Inspection; Laboratory tests; Time factors

**ABSTRACT:** Fatigue cracking was first observed at the Yellow Mill Pond Bridge on the Connecticut Turnpike (I-95) in 1970. Fatigue crack growth resulted in complete fracture of a tension flange in one of the girders. Smaller cracks were discovered in several other beams. Fatigue cracking started at the end weld of cover plates welded on the rolled section, which form the longitudinal girders of the bridge structure. Several inspections were made between 1970 and 1979. The stress range due to the traffic was recorded in 1971, 1973 and 1976. Maximum stress ranges as high as 10.5 ksi (72.4 MPa) were measured at the end weld of the cover plates. The results from the bridge observations are compared with laboratory fatigue test data on small size and full size cover plated beams. The laboratory tests and analytical predictions of crack growth agree well with the observations made on the Yellow Mill Pond Bridge.

**REFERENCE:** Fisher, John W., Slockbower, Robert E., Hausamman, Hans, and Pense, Alan W., "Long Time Observation of a Fatigue Damaged Bridge," *Journal of the Technical Councils*, ASCE, Vol. 107, No. TC1, **Proc. Paper 16166**, April, 1981, pp. 55-71

## 16171 COMPUTER ANALYSIS AND DESIGN OF STRUCTURES

**KEY WORDS:** Computer analysis; Computer applications; Computerized design; Computer programs; Computers; Concrete slabs; Piping systems; Steel frames; Structural analysis; Structural design; Transmission towers

**ABSTRACT:** The advances of computer technology can be seen almost daily in both everyday life and in engineering. The purpose of computer programs or "software engineering" is to make the enormous computing power of today's hardware available to the engineer, relieving the design engineer from a considerable burden. Computer analysis of structures is an almost perfect tool for today's structural engineer. Some of the theory underlying structural analysis and design programs are presented, as are some aspects that relate directly to the use of such programs. The major capabilities of a number of widely used programs are summarized, and the following examples illustrate points of interest: steel frame analysis and design, concrete flat slab design, piping system analysis, and transmission tower design.

**REFERENCE:** Meyer, Christian, "Computer Analysis and Design of Structures," *Journal of the Technical Councils*, ASCE, Vol. 107, No. TC1, **Proc. Paper 16171**, April, 1981, pp. 73-94

## 16168 METRICATION AT RESOURCES SERVICE

**KEY WORDS:** Construction; Construction costs; Contractors; Costs; Governmental role; Metric system; Training; Water resources

**ABSTRACT:** The Water and Power Resources Service, formerly the Bureau of Reclamation, has begun construction of a number of major projects using International System (SI) metric units. Experiences of both contractor and government forces are related. Brief training courses in SI metric units were used, and a metric manual was developed to allay the fears of employees who were reluctant to use SI metric units because of their lack of familiarity. Few problems developed, although suppliers did create a problem due to their reluctance to furnish items in SI metric units. Cost increases due to metrication are included.

**REFERENCE:** Lewandowski, E. R., "Metrication at Water and Power Resources Service," *Journal of the Technical Councils*, ASCE, Vol. 107, No. TC1, **Proc. Paper 16168**, April, 1981, pp. 95-100

## 16169 GOLDEN GATE BRIDGE: DECK INVESTIGATION

**KEY WORDS:** Bridge decks; Bridge inspection; Bridge maintenance; Bridges (suspension); Chlorides; Concrete deterioration; Corrosion; Cracking; Investigations; Orthotropism

**ABSTRACT:** Detailed investigations have found widespread defects and local failures in the roadway slab of the Golden Gate Bridge. Cracking exists throughout over transverse reinforcing bars. Concrete cores established chloride ion contamination beyond the safe threshold level, and electrical potential measurements confirmed the presence of reinforcing steel corrosion. Rehabilitation studies indicated that deck replacement was economically preferable. Of the many deck types investigated, an orthotropic deck section was selected because of savings in dead load, easier erection under traffic conditions, and lower maintenance cost.

**REFERENCE:** Reilich, Harry D., and Stahl, Frank L., "Golden Gate Bridge: Deck Investigation," *Journal of the Technical Councils*, ASCE, Vol. 107, No. TC1, **Proc. Paper 16169**, April, 1981, pp. 101-116

## 16165 METHODS OF ACCESS TO COMPUTING FACILITIES

**KEY WORDS:** Computer applications; Computer programs; Computer systems hardware; Consultants; Manuals; Service centers

**ABSTRACT:** This paper will be a chapter in the proposed ASCE "Introductory Manual of Computer Services." In this section, the possible methods of access to various computer facilities are explained. The many phases in the computer solution to a typical problem are briefly described, and the sometimes conflicting roles of service bureaus, consultants, and in-house facilities are reviewed. Finally, some suggestions and techniques are presented for getting started in the use of computing machinery to solve engineering problems.

**REFERENCE:** McCormick, John M., "Methods of Access to Computing Facilities," *Journal of the Technical Councils*, ASCE, Vol. 107, No. TC1, **Proc. Paper 16165**, April, 1981, pp. 117-124

## 16182 ACQUIRING A COMPUTER

**KEY WORDS:** Computer components; **Computers;** Computer storage devices; **Computer systems hardware;** **Contracts;** Evaluation; Financing; **Project management;** **Project planning**

**ABSTRACT:** The entire process of establishing an in-house computer center is developed as a typical civil engineering design project requiring a formal approach of: (1) Sound engineering investigation, evaluation and preparation; and (2) sound business justification, contract negotiation and financing. General, step-by-step, guidelines and important points of consideration are presented to assist a potential computer consumer in the task of computer acquisition. The guidelines begin with the justification of a computer purchase, and they proceed through vendor market research, request for proposals, vendor selection, contract negotiation and preparation for the computer's arrival. Topics discussed and recommendations given include hardware and software needs, computer performance specifications, benchmarking, price and contract term negotiations, maintenance agreements and software development.

**REFERENCE:** Tonia, Elias C., "Acquiring a Computer," *Journal of the Technical Councils, ASCE*, Vol. 107, No. TC1, **Proc. Paper 16182**, April, 1981, pp. 125-142

## 16196 SEISMIC STRENGTHENING OF A POWER SYSTEM

**KEY WORDS:** Cost control; Cost effectiveness; **Cost savings;** **Earthquake damage;** **Earthquake engineering;** **Earthquakes;** Hydroelectric powerplants; **Power system stability;** **Seismic design;** Thermal power plants; Transmission lines

**ABSTRACT:** Low cost measures are presented that could prevent damage to power systems during future seismic events. In a high seismicity region, a cost increase of few percent can reasonably be expected to provide adequate seismic resistance. In a region of low or moderate seismicity, however, the earthquake probabilities are so low that the increase of construction costs which can be justified is almost nil because the probabilities are so low. The key words regarding earthquake resistance are: anchor, brace, separate, guide, cushion, latch, limit, select and plan. The effects of earthquakes on hydroelectric power plants, thermal power plants, transmission systems, and distribution systems are reviewed.

**REFERENCE:** Steinhardt, Otto W., "Low Cost Seismic Strengthening of Power System," *Journal of the Technical Councils, ASCE*, Vol. 107, No. TC1, **Proc. Paper 16196**, April, 1981, pp. 143-151

## 16203 COMPUTER HARDWARE FOR CIVIL ENGINEERS

**KEY WORDS:** Binary digits; Coded signs; **Communication systems;** Computer graphics; Computer languages; **Computer storage devices;** **Computer systems hardware;** **Computer terminals;** Error detection codes; **Interfaces;** Magnetic tapes; **Minicomputers;** Numerical calculations; Terminals

**ABSTRACT:** Computer hardware as it pertains to civil engineering is explained, and the fundamentals of the binary system and both numerical and character encoding schemes are presented. Computer configurations, including primary and secondary storage, are examined; a general classification hierarchy is established. An extensive overview of computer peripherals is provided, encompassing the following: communications and interfacing; terminals; lineprinters; magnetic tape, disk and drum storage; plotters; cardreaders; and analog-to-digital interfaces. Computer reliability is considered with an emphasis on error detection and recovery. Numerous terms and measurement quantities are defined.

**REFERENCE:** Rooney, Martin F., "Computer Hardware for Civil Engineers," *Journal of the Technical Councils, ASCE*, Vol. 107, No. TC1, **Proc. Paper 16203**, April, 1981, pp. 153-168

## 16210 INSTITUTE FOR COMPUTERS IN ENGINEERING

**KEY WORDS:** Communication systems; Computer programming; Computers; Computer systems programs; Engineering services; Engineering societies; Project feasibility; Project management; Project planning; Project summaries

**ABSTRACT:** A business plan is for proposed for the establishment of a National Institute for Computers in Engineering (NICE). It also identifies potential sources of funding for the NICE project. NICE will be an independent, not-for-profit organization comprising engineering-related professional societies. Its prime purpose will be to provide an information service which will assist in promoting the effective use of computers and computer software as tools of the practicing engineer. NICE will provide services for a fee to the practicing engineer. The principal service will be the provision of information on computer software based on systematic methods of information collection, computerized storage and retrieval. This paper represents the work of members of the Computer Practices Committee, ASCE, in conjunction with members of the Society for Computer Applications in Engineering, Planning and Architecture.

**REFERENCE:** Beck, Charles F., Chrm., "Business Plan for the Establishment of National Business Institute for Computers in Engineering (NICE)," *Journal of the Technical Councils*, ASCE, Vol. 107, No. TC1, **Proc. Paper 16210**, April, 1981, pp. 169-189.

## 16214 SEISMIC DESIGN OF LIQUID STORAGE TANKS

**KEY WORDS:** Deformation; Design criteria; Dynamics; Dynamic stability; Finite element method; Hydrodynamics; Impulsive loads; Mechanical analysis; Models; Seismic stability; Seismic studies; Storage tanks; Tanks (containers)

**ABSTRACT:** A simple and sufficiently accurate method for estimation the seismic response of cylindrical liquid storage tanks is presented. A mechanical model, which takes into account the deformability of the tank wall is examined; it is based on the results of a finite element analysis of the liquid-shell system. The parameters of such a model are displayed in charts that facilitate the calculations of the effective masses, their centers of gravity, and the periods of vibrations. Detailed numerical examples are presented to illustrate the applicability of this model in predicting the maximum seismic response by means of response spectrum. Comparison with the "exact" solution of the problem confirms the validity of the method.

**REFERENCE:** Haroun, Medhat A., and Housner, George W., "Seismic Design of Liquid Storage Tanks," *Journal of the Technical Councils*, ASCE, Vol. 107, No. TC1, **Proc. Paper 16214**, April, 1981, pp. 191-207

## U.S. CUSTOMARY-SI CONVERSION FACTORS

In accordance with the October, 1970 action of the ASCE Board of Direction, which stated that all publications of the Society should list all measurements in both U.S. Customary and SI (International System) units, the following list contains conversion factors to enable readers to compute the SI unit values of measurements. A complete guide to the SI system and its use has been published by the American Society for Testing and Materials. Copies of this publication (ASTM E-380) can be purchased from ASCE at a price of \$3.00 each; orders must be prepaid.

All authors of *Journal* papers are being asked to prepare their papers in this dual-unit format. To provide preliminary assistance to authors, the following list of conversion factors and guides are recommended by the ASCE Committee on Metrication.

To convert	To	Multiply by
inches (in.)	millimeters (mm)	25.4
feet (ft)	meters (m)	0.305
yards (yd)	meters (m)	0.914
miles (miles)	kilometers (km)	1.61
square inches (sq in.)	square millimeters (mm <sup>2</sup> )	645
square feet (sq ft)	square meters (m <sup>2</sup> )	0.093
square yards (sq yd)	square meters (m <sup>2</sup> )	0.836
square miles (sq miles)	square kilometers (km <sup>2</sup> )	2.59
acres (acre)	hectares (ha)	0.405
cubic inches (cu in.)	cubic millimeters (mm <sup>3</sup> )	16,400
cubic feet (cu ft)	cubic meters (m <sup>3</sup> )	0.028
cubic yards (cu yd)	cubic meters (m <sup>3</sup> )	0.765
pounds (lb) mass	kilograms (kg)	0.453
tons (ton) mass	kilograms (kg)	907
pound force (lbf)	newtons (N)	4.45
kilogram force (kgf)	newtons (N)	9.81
pounds per square foot (psf)	pascals (Pa)	47.9
pounds per square inch (psi)	kilopascals (kPa)	6.89
U.S. gallons (gal)	liters (L)	3.79
acre-feet (acre-ft)	cubic meters (m <sup>3</sup> )	1,233

# JOURNAL OF THE TECHNICAL COUNCILS OF ASCE

## SEISMIC DESIGN OF PUMPING PLANTS<sup>a</sup>

By Walter F. Anton,<sup>1</sup> F. ASCE

(Reviewed by the Technical Council on Lifeline Earthquake Engineering)

### INTRODUCTION

Pumping plants serving water supply and sewage systems are important lifeline facilities and should remain in operation or be readily repairable following a damaging earthquake. Water distribution pumping is necessary to maintain sufficient storage to fight fires and to provide minimum potable water for consumption and other critical disaster recovery needs (e.g., drinking water, food preparation, hospital usage, sanitation, etc). The outage of sewage lift stations can result in serious health hazards from sewage spills; outage of sewage treatment plant pumping stations can result in serious pollution of receiving waters, which can seriously affect downstream water supplies, or cause environmental damage, or both.

Structures similar to those used to house pumping equipment and piping have been damaged by earthquakes when not properly designed to resist seismic forces. The 1971 San Fernando Earthquake and other large earthquakes have demonstrated that equipment and piping similar to that found in pumping plants can be damaged by earthquakes; typical damage is described in this paper.

Relatively little has been presented in the technical literature and limited written practices cover the subject of seismic design of pumping plants. Consequently, a survey was made of 20 consultants and 15 utilities in an attempt to identify current private and governmental engineering practices for the seismic design of these facilities. Slightly more than half responded; those with useful information contained in this paper are identified. Several respondents had no specific seismic design practices for pumping plants.

<sup>a</sup>Presented at the April 14-18, 1980, ASCE Annual Convention and Exposition, held at Portland, Ore. (Preprint 80-096).

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This paper includes pertinent portions of the East Bay Municipal Utility District's (EBMUD) engineering standard practice used by its staff for determining the minimum design requirements for new or upgraded water supply facilities and a series of additional structural and support system design recommendations. The resulting seismic forces are somewhat conservative, reflecting the vulnerability of EBMUD transmission and distribution pumping plants to: (1) Two major active faults through its service area capable of producing earthquakes of 7.5 magnitude; and (2) the nearby San Andreas Fault capable of producing an 8.5 magnitude earthquake.

#### **SUSCEPTIBILITY OF PUMPING PLANTS TO SEISMIC DAMAGE**

In their article (4), Roland Sharpe and Ronald Gallagher identified typical earthquake damage to mechanical and electrical equipment caused by the 1971 San Fernando Earthquake. Illustrations applicable to pumping plants included:

1. Many pump and motor units were damaged when they slid off their mountings; other motors moved sufficiently to detach conduits and wiring.
2. A butterfly valve on a 12-in. (300-mm) diam condenser water line broke. There were many instances of damage to pipe hangers. In some cases, piping hung from roof framing tended to be more rigid than the building frame to which it was attached. Extreme building sidesway caused severe distress to pipe hangers, many of which pulled completely away from the roof framing. Some of the damage sustained by pipe hangers could also be attributable to vertical earthquake forces.
3. A spring-type vibration isolation device failed on a damaged air-handling unit—a common mode of failure. Damaged heating, ventilating, and air-conditioning units generally fell off vibration isolation devices, bending or severing ducts, conduits, or control wiring.
4. Rail-mounted transformers and other equipment without positive means of resisting lateral support slid laterally on their foundation pads, causing extensive damage to conductors. Even welded studs at the base plate of a filter reactor broke.
5. Control panels installed without adequate anchorage overturned or slid on their foundations.
6. Suspended ceilings (including attached lighting fixtures) and pendant-type light fixtures hung on rods or wires from floors and roofs were damaged.

Sharpe and Gallagher also identified a number of the more salient lessons learned from the San Fernando Earthquake that are applicable to pumping plants:

1. Mechanical and electrical equipment, and their supports and connections must be designed to withstand realistic seismic forces if sliding or overturning of equipment, disruption of utility service, or other possible costly damage is to be avoided or minimized.
2. Ceilings, light fixtures, and other "nonstructural" elements should be designed to resist seismic forces without collapse.
3. Proper seismic design should consider the simultaneous effects of both horizontal and vertical earthquake forces.

4. Elevator equipment emergency power supply systems should be given especially detailed treatment in seismic design.

5. For equipment located in structures, the possibility of damage resulting from the interaction of the structure and equipment should be considered. Components of large diameter piping systems, especially pipe hangers, that cannot accept the loads imposed on them as a result of interstory building displacements are particularly vulnerable to this type of damage.

6. Equipment having supporting members and connections of brittle materials are very susceptible to damage.

#### GENERAL CONSIDERATIONS

Although engineers cannot design an earthquake-proof pumping plant, they should try to minimize damage during strong ground acceleration which may occur during the life of the structure.

Each pumping plant has its own special problems and must be treated individually, applying a degree of conservativeness depending on particular circumstances such as: (1) Availability of alternative sources of energy; (2) ability to isolate damaged areas of the distribution systems to ensure continued operation of the system; (3) availability of sufficiently trained repair personnel, supplies, and materials; and (4) mutual assistance between utilities.

A typical approach to the seismic evaluation of a facility can be found in the general requirements used by one of the respondents:

All equipment, piping, tanks, panels, etc., and their supports and anchorages shall be designed to resist seismic loading as required by the 1976 edition of the Uniform Building Code for Seismic Zone 3. To facilitate the Engineer's review of the shop drawings, computations signed by a California licensed civil engineer (or complete, applicable and current test data from a recognized testing laboratory) shall be submitted with the shop drawings showing compliance with this requirement. Adequate information including weight, magnitude and location, dimensions, connection, details, etc., shall be provided to evaluate the design.

Faithful adherence to code provisions will be of little value without sound engineering judgment applied during the selection of materials, structural system layouts, and design connections. Attention to these details will significantly minimize future earthquake damage.

Manufacturers of mechanical and electrical equipment have not generally offered seismic-qualified designs as standard options in their product lines. Mechanical equipment, such as pumps and valves, are considered to be intrinsically designed to resist large forces and thus require no special analysis for earthquake loads. Some respondents said they do not require electrical designs to include special considerations for seismic occurrence other than to require that equipment be built to industry standards (letter from Robert B. Jansen to the writer); other respondents indicated more stringent requirements.

Manufacturers will conduct seismic tests on their equipment that will qualify the specific item for seismic withstand at costs of \$3,000/test-\$6,000/test. Repair costs are extra if the equipment is damaged.

One of the most important factors in seismic design is the value adopted for ground acceleration. Design ground acceleration adopted for a project should consider the degree of risk, safety factor, earthquake probability, life of structures, and response spectrum.

The necessity for an adequate geotechnical investigation cannot be over-emphasized. The approach of the Los Angeles Department of Water and Power (as revealed in a letter from Val Lund to the writer) is that once a preliminary pumping station site has been selected, a thorough geologic and seismic study and a foundation investigation are conducted. Major facilities are constructed on bedrock or on a compacted fill on bedrock. The relative locations of all known major fault systems with respect to the site are determined. A geology report is then prepared and submitted to the Department of Building and Safety for approval, which outlines any special foundation problems which must be considered in the design. During construction, the foundation is again examined to ensure that the footings are on firm material.

Facilities designed to resist earthquake forces under the Uniform Building Code (UBC) are considered to be able to: (1) Resist minor earthquakes without damage; (2) resist moderate earthquakes without structural damage, but with some nonstructural damage; and (3) resist major earthquakes at the intensity of the strongest experience in the region, without collapse, but with some structural as well as nonstructural damage.

It would be preferable to use a more severe criterion for important pumping plants. For example, the aforementioned third point would be tightened up and modified to read "Resist . . . in the region, without collapse but with some structural deformation, negligible structural damage, and some nonstructural damage."

The Water and Power Resources Service's approach (as revealed in a letter from Robert Jansen to the writer) is noteworthy for the following points:

1. The design basis earthquake is used to determine structural response conditions. This earthquake would be the one likely to occur only once during the economic life of the structure.

2. Under loading from this event, the plant would be designed to sustain the earthquake with repairable damage but structures, systems, and components vital to safety would remain functional. The degree of damage which would be acceptable could be based on an economic analysis or estimate of the cost of repair versus the initial cost to control the damage.

3. The severity of the earthquake hazard is evaluated and a judgment is made whether the plant structures have features which warrant a dynamic analysis.

4. Many pumping plants are extremely rigid box-shaped structures, possibly buried in the ground, with no superstructure. These very short period structures are designed using the appropriate percentage of gravity applied to the body forces to produce an equivalent static load.

5. A dynamic analysis is required for more complex structures which may include cantilevered superstructures with large masses, such as overhead cranes or heavy roofs.

#### **EBMUD MINIMUM SEISMIC REQUIREMENTS FOR PUMPING PLANTS**

Although somewhat conservative because of EBMUD vulnerability to major

earthquakes in the San Francisco Bay Area, the following formulas and guidelines are utilized to design or analyze pumping plant structures and internal equipment and piping. Sound engineering judgment and the proper application of structural theory accompany the requirements to make them fully effective.

In no case are the design seismic forces used less than the requirements of the current edition of the UBC. The seismic requirements specified in the following are based on the 1979 edition of the UBC, with modified  $Z$  and  $I$  factors as tabulated in the following.

Pumping plants (including nonstructural components) are designed and constructed to resist stresses produced by lateral and vertical seismic forces as provided in the following. The horizontal force is applied on buildings at each floor or roof level above the foundation and stresses computed from those loads. The forces are assumed to act in any horizontal direction. The vertical seismic forces are applied to the design of horizontal framing systems, columns and walls and their anchorage to the foundations. The horizontal and vertical seismic forces are assumed to act concurrently. Vertical seismic forces are assumed acting either up or down.

**Horizontal Lateral Force and Distribution of Force.**—The following is information on horizontal lateral forces and their distributions:

1. Total Lateral Force and Distribution of Lateral Forces—Every building is designed and constructed to withstand a minimum total lateral seismic force in accordance with the following formula:  $F_A = ZIKCSW_f$ , in which  $Z$  = seismic zone coefficient (see Table 1);  $I$  = importance factor (see Table 2);  $K$  = numerical coefficient from Table 23-I of the UBC;  $C$  = numerical coefficient for base shear from Section 2312(d) of the UBC, and  $C$  need not exceed 0.12;  $S$  =

TABLE 1.—Seismic Zone Coefficient,  $Z$  (See Figs. 1-3 in Chapter 23 of the UBC)

Seismic zone (1)	$Z$ (2)
1	3/16
2	3/8
3	3/4
4	1 to 1-1/4

Note: The value of  $Z$  for Zone 4 varies with the distance of the facility from the major active Hayward and Calaveras Faults. The minimum value is used when the facility is five or more miles away from either of these faults. The maximum value is used when the facility will be adjacent to either of these faults.

TABLE 2.—Importance Factor,  $I$

Variable (1)	$I$ (2)
Transmission and sole source pumping plants	1.50
Pumping plants with alternate supply	1.33

numerical coefficient for site-structure resonance from Section 2312(d) of the UBC, and  $CS$  need not exceed 0.14; and  $W_d$  = total dead load.

The total lateral force is distributed in proportion to the mass and height of the elements of the building as assigned in Chapter 23, Section 2312(e), of the UBC. Where wind load, as specified in the UBC would produce higher stresses, this load is used in lieu of the loads resulting from earthquake forces.

2. Lateral Force on Parts or Portions of Buildings and Mechanical and Electrical Supports—The lateral seismic forces on architectural, mechanical, and electrical components and systems are determined according to the procedure set forth in Ref. 5, Chapter 8.

The lateral seismic force  $F_p = A_s C_c P a_x W_c$ , in which  $A_s$  depends on site seismicity = 0.4–0.5 within distribution area (varies like the  $Z$  value in Table 1), and equals 0.3 in the Central Valley and Sierra foothills. The variable  $C_c$  = coefficient determined from Table 8-C of Ref. 5;  $P$  = the performance criterion varying between 1.5 and 0.5, depending on the seismic hazard exposure group (Ref. 5), and also depending on whether the component is part of a lifeline system or if there is a risk to health and safety (from Table 3). The variable  $a_x$  = the amplification factor related to the response of a system or component as affected by the type of attachment. The value equals 1.0 if

TABLE 3.—Performance Criteria (see Table 8-A of Ref. 5)

Designation* (1)	Performance characteristics level (2)	$P$ (3)
S	Superior	1.5
G	Good	1.0
L	Low	0.5

\*Table 8-C of Ref. 5.

fixed or directly attached to buildings or has a resilient mounting system with a seismic-activated restraining device. Otherwise, the value depends on the fundamental period of the building and the component, as shown in Chapter 8 of Ref. 5 (except that the fundamental period of the building is determined from the UBC). The variable  $a_x$  = the amplification factor related to the variation of the response in height of the building (see formula 8-3 of Ref. 5); and  $W_c$  = the weight of the component.

**Vertical Seismic Force and Distribution of Force.**—Pumping plant structures are designed to withstand a total seismic vertical force acting at each floor above ground at the center of mass equal to one half of the lateral force,  $F_h$ , in seismic zone 4, and one fourth of the lateral force,  $F_h$ , in other seismic zones.

Equipment anchor bolts and related connections are to be capable of supporting at least the weight of the equipment vertically upward and at least twice the weight vertically downward. [Others advocate the use of vertical seismic forces equaling two-thirds of the horizontal seismic forces (4).]

#### DETERMINATION OF SEISMIC REQUIREMENTS BY OTHERS

Most of the consultants and utilities responding to the survey of current

practice indicated that they used either the current UBC or local building code. Several consultants designed or evaluated particularly important structures in major seismic regions by the use of a site-specific seismic response spectra analysis.

The Los Angeles Department of Water and Power pumping station buildings are analyzed as shear wall buildings and designed under the provisions of the Los Angeles City Building Code. Pumping stations are considered to be "essential facilities" and, therefore, are designed to resist a total horizontal lateral seismic force of  $0.28 W$ , in which  $W$  = the total dead load. This force is assumed to act nonconcurrently in the direction of each of the main axes of the building (5).

One respondent, who adopted a minimum ground acceleration of  $0.20 g$  for all projects in California, pointed out that this factor is very important as the construction cost goes up as the factor increases—up to approx  $0.30 g$ , only minor cost increases occur; over this value, the cost increase goes up rapidly.

An interesting example of a major pumping plant given special seismic design considerations is the Oso Pumping Plant, designed by Bechtel Inc., which is an integral part of the California Aqueduct system (8). The plant has a  $3,100\text{-cfs}$  ( $87\text{-m}^3/\text{s}$ ) capacity and is located 40 miles (60 km) west of Lancaster, supplying water to the Los Angeles area. The plant is in close proximity to the San Andreas fault and sits on  $100 \pm \text{ft}$  (30 m) of alluvium deposit, which is a competent foundation soil; however it has a high ground-water table. There is no foundation rock within a practical distance. Special seismic design considerations were as follows: (1) The steel superstructure was designed to withstand  $0.5 g$  of horizontal static force; (2) the foundation was designed against sliding for  $0.2 g$  of equivalent static force plus normal operating loads; (3) the design used resilient material in lieu of grout for filling joints between buried prestressed concrete cylinder pipe; (4) the design provided a siphon breaker at the pipe outlets to prevent backflow from the upper canal during interruption of pumping operation, which could be caused by severe earthquake; (5) the main transformer was anchored to the base pad by bolting; the base pad anchored to the soil with belled caissons; and (6) the design provided for a pair of special sleeve-type pipe couplings and an expansion joint at each discharge pipe/plant interface to allow relative displacements.

#### MECHANICAL AND EQUIPMENT SUPPORT RECOMMENDATIONS

Many of the respondents to the survey of current practice indicated that special seismic provisions were made for equipment and pipe support systems. In addition to the aforementioned recommended minimum seismic force requirements, the mechanical and equipment support systems should be designed considering the following:

1. Support arrangements should be designed so that equipment will not topple or shear away from its mounts; ductile materials, such as mild steel, are used to provide tough performance. Brackets, anchors, etc. should be ductile so that they can bend without breaking and continue to carry load and absorb energy. Agencies such as the Los Angeles Department of Water and Power and the California Department of Water Resources (DWR) have used Belleville

washers to reduce the natural frequency (and increase critical damping) of electrical substation equipment support systems mounted on brittle materials, such as insulating porcelain.

2. Connections should be as strong as the adjoining members themselves, or be able to bend or give, rather than break.

3. The interaction of piping and structures or fixed equipment must be considered because inflexible pipes connected to relatively massive, rigid appurtenances and structures or to two different structural elements can be broken or damaged by differential displacements due to foundation rocking or differential foundation settlements or displacements caused by vibration-induced soil consolidation. Stiff piping systems that may resist the sidesway of the more flexible structure to which they are attached should be avoided.

4. Since equipment flexibly mounted in buildings or structures can have its response to earthquake motion considerably amplified, it should be rigidly secured or braced, yet avoiding problems from vibration transmission and thermal movement.

5. Care should be taken to assure that the equipment supporting system can accommodate realistic interstory displacements which could result in distress to equipment and supports, particularly when the equipment system is rigid in comparison to the building and tends to act as a lateral force-resisting element of the building.

6. Although it is likely that the structural engineer will perform the design, seismic restraints for piping, ducts, equipment, etc. should be shown on the drawings on which the piping, ducts, equipment, etc. are shown. The reviewer of the shop drawings must be well-qualified and adequately involved in the design phase. An alternative permits the manufacturer, or contractor, or both, to detail the restraints following the engineer's specified criteria—a critical review follows.

#### DESIGN CONSIDERATIONS FOR EMERGENCY CONDITIONS

**Equipment Protective Devices.**—The following are possible equipment protection devices:

1. Pressure switches—provided on the discharge piping to shut down pumps on low pressure (ruptured pipelines) or on high pressure (collapsed or blocked pipelines).

2. Temperature switches—provided to sense high discharge piping temperature, as would occur from continuous water recirculation through a failed bypass pump control valve, a failed high discharge pressure switch, or a closed isolating valve.

3. Motor winding temperature detectors—provided to sense overloaded motor conditions, or severely unbalanced electric power phase and voltage conditions.

4. Vibration detectors—provided on a few of the larger motors to alarm on continuous low magnitude vibrations, and to shut down the pumps on higher magnitude vibrations. Time delay relays are used to prevent shut down of operating motors during momentary seismic disturbances. Bearing problems often can be found by these devices.

**Valving and Connections.**—The following are possible valves and connections which could be used in emergency conditions:

1. Pressure relief/pump control bypass valves—provided on the discharge of pumps to serve a dual function: (a) Normal operations—the pump control function is used to substantially reduce the pipeline hydraulic pressure surges that occur when pumps are stopped; and (b) emergency conditions—the pressure relief function is used to allow continuous pumping to provide a supply of water in the event a storage reservoir is removed from service. During such events, the pump capacity often exceeds the instantaneous water consumption from the distribution system and the valve opens sufficiently to bypass the unused capacity back to the pump suction while maintaining a constant discharge pressure.
2. Isolating valves are located to be accessible in emergencies.
3. Pumping connections outside the pumping structure are provided so that engine-driven portable pumps can be used during times the installed pumps cannot be used. These connections most often consist of a pair of fire hydrants separated by a closed gate valve between the higher and lower pressure zones.

**Other Considerations.**—Other considerations are as follows:

1. Although the Los Angeles Department of Water and Power pumping units and other necessary equipment are designed to withstand the maximum acceleration and deflections of the structure without disrupting operations, most of their larger pumping stations include an engine-driven pump which can be utilized to maintain pumping capability if the power service is disrupted (as revealed in a letter from Val Lund to the writer).
2. Critical equipment such as fire pumps and emergency generators should be located for minimum chance of seismic damage.

#### **FLEXIBLE CONNECTION AT STRUCTURE/BURIED PIPELINE INTERFACE**

One of the more important seismic design features is the provision for some form of flexible connection at the interface between the pumping plant structure and the connected buried pipelines. Nearly half of the respondents to the current practice survey indicated that specific steps are taken to provide such flexible connections.

The EBMUD currently uses three steel ball joints per pipeline in its pumping plants and reservoir valve pits; these allow 6 in. (150 mm) of relative movement in vertical and horizontal directions (see Fig. 1). The joints are located approx 4 ft (1.2 m) from each elbow, as shown, permitting the vector of movement in any direction to be as much as 0.9 ft (275 mm). The ball joint is oriented so that flow will be from the ball side toward the socket in order to minimize the pressure drop. Known manufacturers of ball joints include Barco and Chiksan. Alternate designs considered and rejected included rubber joints and bellows-type expansion joints.

The EBMUD value engineering study for a valve pit with 12-in. (300-mm) diam pipe resulted in a 33% potential saving with the use of rubber joints consisting of an elbow, four retaining rings, and two short pieces of a rubber

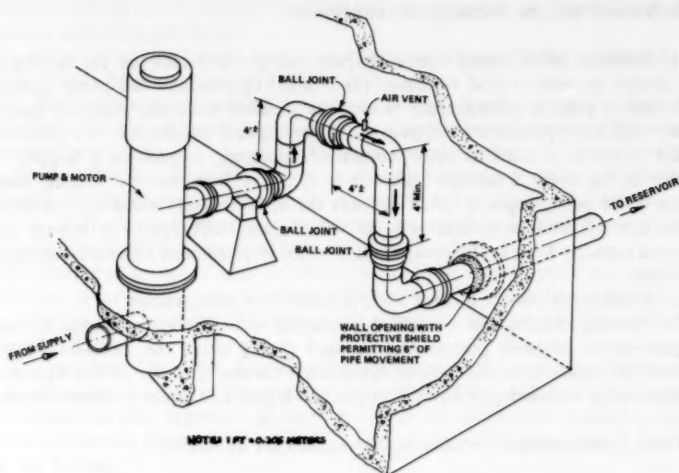


FIG. 1.—Ball Joint-Type Flexible Connection

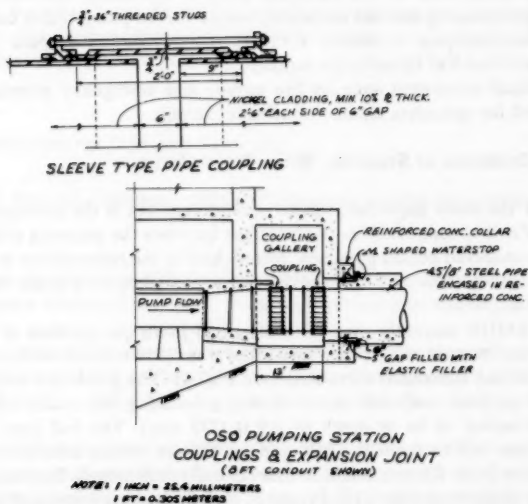


FIG. 2.—Schematic Cross Section of 8-ft Pipe Connection and Detail of Sleeve-Type Pipe Coupling

piping similar to that used in unloading oil tankers. However, the rubber piping was far too stiff to permit 6 in. (150 mm) of movement. Furthermore, the maximum size of rubber pipe was 12 in. (300 mm) in diameter and many inlet-outlet lines are larger.

The EBMUD original flexible connection design consisted of a connected pair of bellows-type expansion joints in series. The system was to be located immediately outside of a pumping plant. Each corrugated bellows was made of thin stainless steel. The expansion joint manufacturer did not recommend use of more than one bellows and district staff was not satisfied that a single bellows would permit sufficient relative movement. In a typical 8-in. (200-mm) size, design end movement was 1-1/4-in. (32-mm) lateral and 3-in. (75-mm) axial for the pair of joints, which appeared promising. Small misalignments during construction and minor piping settlements caused immediate deformations similar to column failure; this design was therefore abandoned.

The Bechtel Inc. design at the DWR Oso Pumping Plant included an interesting flexible connection which was a pair of special sleeve-type pipe couplings and an expansion joint at each discharge pipe/plant interface to allow for relative displacements. The discharge pipes were 4.5 ft (1.4 m) and 8 ft (2.4 m) in diameter. The objective is to provide relative displacements of 6 in. (150 mm) parallel to the pipe and 3 in. (75 mm) perpendicular to the pipes. These couplings were in a special 13-ft (4.0-m) wide coupling gallery which is a separate room outside the plant building. The gallery was separated from plant equipment by water-tight hatch doors. A schematic cross section of one of the 8-ft (2.4-m) pipe connections and a detail of the sleeve-type pipe coupling is shown in Fig. 2.

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#### APPENDIX II.—NOTATION

*The following symbols are used in this paper:*

- $A_v$  = factor depending on site seismicity;
- $a_c$  = amplification factor related to the response of a system or component as affected by type of attachment;
- $a_x$  = amplification factor related to the variation of the response in height of building;
- $C$  = numerical coefficient for base shear from UBC;
- $C_c$  = seismic coefficient in formula for determining seismic force on component;

- $F$  = seismic force;  
 $g$  = acceleration of gravity;  
 $I$  = importance factor;  
 $K$  = numerical coefficient from UBC;  
 $P$  = performance criteria depending on seismic hazard exposure group;  
 $S$  = numerical coefficient for base shear from UBC;  
 $W$  = dead load; and  
 $Z$  = seismic zone coefficient.

#### Subscripts

- $c$  = component;  
 $h$  = horizontal;  
 $p$  = part, portion, or component; and  
 $t$  = total.

# JOURNAL OF THE TECHNICAL COUNCILS OF ASCE

## **COST-PLUS CONTRACTOR SELECTION: A CASE STUDY<sup>a</sup>**

By James E. Diekmann,<sup>1</sup> M. ASCE

(Reviewed by the Technical Council on Research)

### **INTRODUCTION**

Evaluating proposals from potential cost-plus contractors is one of the more troublesome aspects of modern contract administration procedures. Unlike fixed price contracts, the owner has no definitive measure, i.e., cost, to use in selecting a contractor. Instead, he must rely on more abstract measures of potential contractor performance. Typically, owners evaluate contractors on the basis of a number of attributes, such as the commercial terms offered by the contractor, his experience, reputation, and skill, and the financial and temporal stability of the firm. Evaluations are made more difficult by the fact that very often owners have many objectives in awarding a cost-plus contract. The selected contractor, in addition to controlling the cost of the project, may be required to satisfy the requirements of an outside regulatory agency, or may have to possess outstanding technical or managerial capabilities.

Both the value theory and the multidimensional utility theory are methodologies which may be appropriately applied to this selection problem. This paper presents the results and conclusions of a study in which the multidimensional utility approach was used. The study utilized a case study approach in which an owner's representative (henceforth, the "decision maker") was faced with selecting a contractor for a hybrid unit/price cost-plus contract.

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## SUMMARY OF THEORY

**Multiple Objective Decision Making.**—The mathematical analysis of decisions is not a new field. Decision scientists trace the field's beginning back to Daniel Bernoulli, who investigated "fair bets" in gambling games in the early 18th century. Traditionally, decision analysis has been concerned with situations in which decision makers must choose between alternatives characterized by one objective. Profit maximization has long been the prime objective of decision theorists in the business world. Lives saved have been the objective of those working in the medical context. In recent years, however, there has been a growing awareness that most decisions cannot be adequately described in terms of a single objective. Businessmen are certainly interested in maximum profits, but they are also concerned about corporate good will, market share, and future growth. Likewise, the medical profession is interested in saving lives, but harmful side effects from and the cost of treatments must also enter into their decision logic.

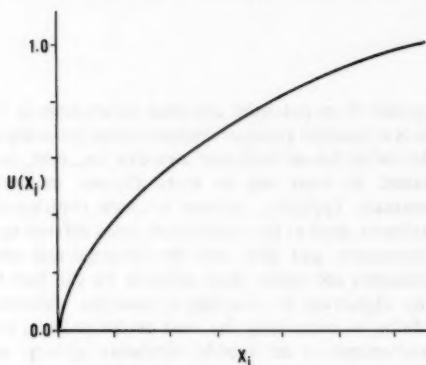


FIG. 1.—Basic Utility Function

The selection of a cost-plus contractor is also a decision characterized by multiple objectives. Owners want to minimize the cost of projects, but also they require contractors to maintain schedules, be quality-oriented, and be safety-minded to mention a few prominent objectives.

**Single Objective Utility Theory.**—One of the most widely used of the single objective decision theories is the concept of cardinal utility, as axiomized by von Neumann and Morgenstern (7). A utility function is a device which quantifies the preferences of a decision maker by assigning a numerical index to varying levels of satisfaction of an objective. The utility of satisfaction in objective  $x$  is denoted by  $u(x)$ . Utility functions are so constructed such that  $u(x) > u(y)$ , if and only if  $x$  is preferred to  $y$ . Further, in situations in which satisfaction is uncertain, utility functions have the property that expected utility can be used as a guide to rational decision making.

In approximate terms, a utility function is a transformation of some level

of contractor performance,  $x_i$ , measured in its natural units into an abstract equivalent level of decision maker satisfaction, as shown in Fig. 1. A utility curve must at once combine the decision maker's preferred attitudes, i.e., does utility increase or decrease with increasing  $x_i$ , and the decision maker's risk attitudes. Theoretically, decision makers are of three distinct types: risk prone, risk neutral, and risk averse. Fig. 2 depicts typical utility curves for each. Numerous studies indicate that most professional decision makers fall in the risk averse category.

**Multi-Objective Utility Theory.**—As previously stated, however, most decisions must be characterized by a number of separate objectives ( $x_1, x_2, \dots, x_n$ ). Accordingly, it is reasonable to attempt to describe a multidimensional utility function:

$$U(X) = u(x_1, x_2, \dots, x_n) \dots \dots \dots (1)$$

Thus, for the two objective cases, if  $u(x_1, y_1) > u(x_2, y_2)$ , then consequence  $(x_1, y_1)$  is preferred to consequence  $(x_2, y_2)$ . The most common formulation of a multidimensional utility function is the additive model:

$$U(X) = \pi_1 u(x_1) + \pi_2 u(x_2) + \dots + \pi_i u(x_i) + \dots + \pi_n u(x_n) \dots \dots \dots (2)$$

in which  $u(x_i)$  = the single attribute utility function of  $x_i$ ; and  $\pi_i$  = a scaling constant for attribute  $x_i$ .

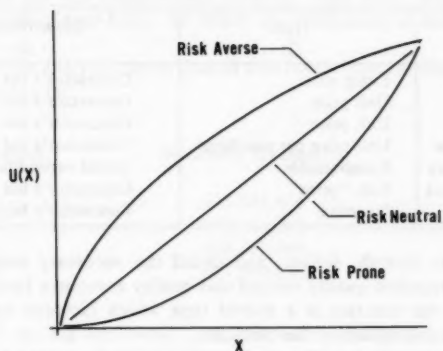


FIG. 2.—Characteristic Utility Functions

An obvious advantage of the additive form is its simplicity. A decision maker need only determine  $n$  one-dimensional utility functions in order to determine the multidimensional  $U(X)$ . In approximate terms, the scaling function,  $\pi_i$ , may be thought of as a weight which measures the relative importance of satisfying a particular objective. Thus, if  $\pi_i = 0.50$  and  $\pi_j = 0.25$ , then  $x_i$  is twice as important as  $x_j$ .

The simplicity of the additive form is not without a price, because additive form implies some rather restrictive independence requirements among objectives. Inasmuch as the nature of independence requirements are somewhat beyond the scope of this paper, the satisfaction of the independence requirements will

be assumed and the interested reader is directed to Ref. 2 for further clarification of independence requirements.

This paper now proceeds to demonstrate the development of an additive utility model for the selection of a cost-plus contractor.

#### CHARACTERISTICS OF TEST CASE

**Project Characteristics.**—The project used as a basis for this study is a large, two-unit nuclear power plant. The estimated final cost of the entire project is approx \$2.3 billion. The project is located in a semirural area, reasonably close to large labor markets. This project, like many nuclear power projects, utilizes the separate contracts approach to construction. In all, there will be more than 40 separate, independent construction contractors employed on the project. The decision maker in this study was the actual owner's representative who was charged with evaluating the contractors. In all, there are four contractors competing for this work, who will simply be called contractors A, B, C, and D.

**Form of Contract.**—The contract chosen for this study is a \$40,000,000 contract for the installation and testing of various electrical systems in the plant. Of the \$40,000,000, approx \$30,000,000 are for labor costs. The specifications require

TABLE 1.—Provisions of Subject Contract

Element (1)	Type (2)	Determined by (3)
Mobilization	Lump sum	Contractor's bid
Material costs	Unit price	Contractor's bid
Other costs	Unit price	Contractor's bid
Labor wage rate	Unit price per man-hour	Contractor's bid
Labor man-hours	Reimbursable	Actual expenditures
Target man-hours	Unit "price"	Contractor's bid
Target fee	Incentive	Contractor's labor efficiency

the contractor to furnish, deliver, and install the necessary materials as well as perform the required quality control and quality assurance functions.

The form of the contract is a hybrid type which includes lump sum, unit price, cost-plus, and incentive fee elements.

The contract provides for a lump sum mobilization payment to the successful contractor. Material cost and other incidental construction expenses are reimbursed via a unit price arrangement. The contract stipulates a total of 192 separate unit price items.

Labor costs are a cost-plus element. Each labor man-hour is reimbursed at a fixed rate. Labor rates for each construction labor craft classification are bid by the contractor and are fixed for the duration of the contract, except for adjustments for increases dictated by craft labor agreements. Therefore, the markup on labor bid by the contractor and the total number of labor man-hours expended by the contractor combine to form the total reimbursement of labor costs under the contract. Although the rate of reimbursement for each man-hour expended is fixed, the total number of man-hours expended is a function of the skill and experience of each individual contractor.

The contract also provides for an incentive fee arrangement based on the total amount of craft labor man-hours expended. The target labor amount is determined by summing individual labor targets for each of the unit price quantities. The contractor essentially bids a target man-hour "unit price." Thus, as the quantities of work vary, the target man-hours also vary. At the completion of the project, if the contractor has performed the work at his target, the contractor's fee is determined as a specified percentage of the total contract labor costs. If the contractor performs the work for fewer man-hours than his target, the fee percentage is increased. If the contractor performs the work for more man-hours than the target, the fee percentage is decreased. A summary of the provisions of the subject contract is supplied in Table 1.

#### CURRENT EVALUATION METHODOLOGY

The owner currently uses a monetary evaluation to select a contractor. To affect the evaluation, the owner attempts to estimate the final cost impact of awarding to a particular contractor. The methodology requires the owner to evaluate the combined effect that the various commercial terms, i.e., fee structure, overhead rates, etc., and contractor performance will have on the final cost of the project. The evaluation of the cost-plus elements is conducted by assuming some standard level of performance for *all* contractors. In this case, the standard performance for the one reimbursable element, craft labor man-hours, is the engineer's estimate of man-hours. To clarify the evaluation, an example is shown in Fig. 3.

As a result of this analysis, the evaluated cost for the four candidate contractors were determined to be:

Contractor	Monetary Evaluation	Rank
A	\$45,231,456	4
B	\$41,623,763	3
C	\$39,567,466	2
D	\$37,269,635	1

Contractor D, having the lowest "cost," would be the preferred choice.

**Limitations of Current Evaluation Procedure.**—This evaluation procedure has three major shortcomings. It: (1) Assumes each contractor will perform equally with respect to the reimbursable elements; (2) doesn't have the capability for incorporating the effects of the qualitative, nonmonetary attributes of the contractor such as experience, skill, and reputation; and (3) does not consider the effects of risk or uncertain contractor performance on the evaluation.

Owners, of course, realize the shortcomings of a purely monetary evaluation. Most owners require prospective contractors to supply qualitative information about their organization and capabilities as well as the quantitative pricing information. Such qualitative information is incorporated into the evaluation in subjective, intuitive, and informal ways. This paper presents a methodology which combines both the qualitative and quantitative aspects of the contractor's proposal, as well as risk/uncertainty, into a single evaluation.

## MULTI-OBJECTIVE UTILITY THEORY EVALUATION

**Value Hierarchy.**—Once an owner has concluded that the contractor selection process is characterized by multiple objectives, that owner must then describe, in absolute terms, his particular objectives. This is a most critical stage in the process. Usually, the owner will quickly discover that each objective is itself composed of a number of subobjectives. To aid the definition of what is included by each objective, it is often helpful to describe the owner's objectives in terms of a value hierarchy. A value hierarchy is a device which describes the means-end relationship between the objectives of the owner and the measurable attributes of the contractor. The concept of a value hierarchy is depicted in Fig. 4.

ITEM	QUANTITY	MATL & OH UNIT PRICE	MATL & OH COST	LABOR TARGET MH	TARGET Mhs	LABOR WAGE
A	100	20	2,000	2	200	-
B	10	150	1,500	30	300	-
C	2,000	4	8,000	0.2	400	-
TOTAL			11,500 (firm)		900 (firm)	\$20/MH (firm)

<u>TOTAL EVALUATION</u>			<u>LABOR EVALUATION</u>
MATL & OH COST	\$11,500		ENGR EST'D Mhs = 1,000 (ASSUMED SPEND Mhs)
LABOR COST	20,000		LABOR COST = 1,000 × \$20/MH = \$20,000
FEE	2,200		<u>FEE EVALUATION</u>
TOTAL	\$33,700		FIRM TARGET = $\frac{900}{1,000} = .9 = 11\%$ fee rate ENGR EST MH = 1,000 (percent of total labor costs)
			$0.11 \times \$20,000 = \$2,200$

FIG. 3.—Current Monetary Evaluation Methodology

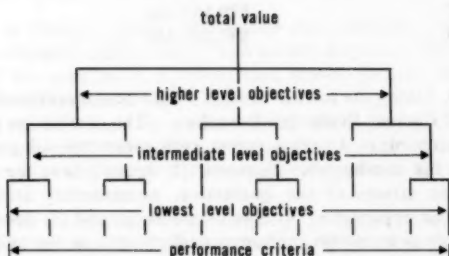


FIG. 4.—Value Hierarchy Concept

**Higher Level Objectives.**—As a starting point, it is essential that the decision maker describe, in global terms, objectives he wishes to satisfy by awarding the contract. It is important that these objectives be of the highest order and that collectively they be exhaustive. No major consideration may be overlooked.

With these considerations in mind, the decision maker in this study described four higher level objectives:

1. **Cost Exposure**—Obviously with a contract of this magnitude (\$40,000,000), the total amount of incurred cost is an important consideration. The fundamental concern of the decision maker in regard to this objective is best described by the question "If the proposal from Contractor X is selected, what is an overall measure of the total monies accruable to that contractor?"

2. **Company Stability**—This, and indeed all of the remaining objectives, address the decision maker's concern for factors other than direct monetary compensation to the selected contractor. This objective assesses the candidate contractor's value in regard to many intangible values and attitudes of a contractor's organization. Considerations such as attitudes toward safety, the cash position (liquidity) of the company, and overall past performance of the company are included.

3. **Quality of Product**—The evaluation process is intended to select a contractor for work on a nuclear power station; thus the reasons for inclusion of this objective are obvious. The decision maker is concerned with not only the quality

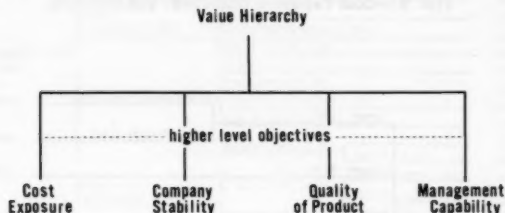


FIG. 5.—Higher Level Objectives

of the technical services at the disposal of the contractor, i.e., engineering disciplines, but also the contractor's ability to provide quality control and quality assurance services which will satisfy the requirements of the Nuclear Regulatory Commission. Inability of the contractor to provide either adequate engineering support or adequate quality assurance and control could result in delays in the construction schedule and ultimately jeopardize the "licensability" of the completed power station.

4. **Management Capability**—The contractor selected for this work is but one of many separate independent contractors to be occupying the construction site at the same time. In this light, the capability to plan, schedule, and execute the work in such a way as to integrate the work effort into the whole, without causing undo delays or disruptions, is essential. Flexibility, capability, and responsiveness of the candidate contractors is required for efficient operation and timely completions. This objective includes factors pertaining to the contractor's site organization which indicates potentially good management capability.

Fig. 5 depicts these four objectives in a hierarchical structure.

**Higher Level Objective Substructures.**—Having established the higher level objectives, the next requirement is to define, in a more precise manner, what

		SCALING FUNCTION % <sub>i</sub>	RANK ORDER % <sub>i</sub>
Fee Structure (.03)	Target Manhours (.50)	.00825	30
	Target Fee Rate (.50)	.00825	31
Fixed Costs (.23)	Average Wage (.40)	.12650	2
	Contr. Plant (.07)	.14300	1
	Construction Equipment (.35)	.00876	28
	Off-Site Fabrication (.15)	.00375	51
	On-Site Prefabrication (.25)	.00626	42
	Innovative Const. Methods (.25)	.00626	43
	Gen. Supt. (.65)	.04648	4
	Experience (.50)	.04648	5
	Nuclear Exp. (.50)	.02503	10
	Craft Supt. (.35)	.02503	11
	Experience (.50)	.00894	26
	Nuclear Exp. (.50)	.01073	20
	Manpower Loading (.25)	.00715	35
	Overtime Usage (.30)	.00894	27
	Shiftwork Usage (.20)	.00715	36
Job Pre-planning (.10)	Quantity Installation Rates (.25)	.00358	52
	Labor Relations Program (.02)	.03300	8
	Management Information System (.01)	.01650	15
Rework Costs (.06)			
Start-Up Costs (.03)			

FIG. 6.—Cost Exposure Objective: Substructure

		SCALING FUNCTION % <sub>i</sub>	RANK ORDER % <sub>i</sub>
Company Stability (.04)	Safety (.25)	.00600	44
	Safety Supervisor (.60)	.00400	49
	Safety Program (.40)	.00800	33
	Current Ratio (.20)	.01200	18
	Number of Years in the Industry (.30)	.01000	22
	Position in the Industry - ENR Top 80 (.25)		

FIG. 7.—Company Stability Objective: Substructure

		SCALING FUNCTION % <sub>i</sub>	RANK ORDER % <sub>i</sub>
Quality of Product (.07)	QA/QC History (.20)	.00700	37
	Generic QA/QC Program (.50)	.00700	38
	Nuclear QA/QC Experience (.50)	.00280	56
	QA Department Reporting Lines (.20)	.00280	57
	Quality Department (.20)	.00280	58
	Nuclear Experience (.50)	.00560	45
	QA Supervision (.40)		
	Qualifications (.50)		
	QA Department Staffing Plan (.40)		
	QA Procedures Matrix (.10)	.00175	59
	QA Procedures (.30)	.00525	47
	QA Implementation Procedures (.50)	.00875	29
	QA Testing Procedures (.10)	.00175	60
	Quality Program (.25)		
	Site Engineering (.35)	.00686	39
Resident Engr. (.70)	Exper. & Qualif. (.40)	.01029	21
	Nuclear Exper. (.60)	.00735	34
Engineering Staff (.30)			

FIG. 8.—Quality of Product Objective: Substructure

is intended by and included within the meaning of each. This process is accomplished by successively dividing and subdividing each higher level objective into related intermediate objectives and finally lower level objectives. In all, 60 different performance criteria were identified during this process. Space considerations preclude detailed analysis of each criterion; however the substructures for each of the higher level objectives are shown in Figs. 6, 7, 8, and 9.

#### FORMULATION OF UTILITY MODEL

The value hierarchy, as developed by the decision maker, specifies a wide variety of criteria by which the potential contractors will be ranked. To complete

		SCALING FUNCTION	RANK ORDER
		$\pi_i$	$\pi_i$
Management Capability (.34)	Site Organization (.09)	Quality (.30)	.00918 25
		Manning Level (.70)	.02142 12
	Project Manager (.35)	Managerial Experience (.60)	.07140 3
		Nuclear Experience (.25)	.02975 9
		Education & General Qualifications (.10)	.01190 19
		Total Industrial Experience (.05)	.00395 50
	Corporate Management (.01)		.00340 53
	Exped. Procurement (.07)	Function (.20)	.00476 48
		Reporting Structure (.40)	.00952 23
		Size of Staff (.40)	.00952 24
	Project Control (.08)	Function (.20)	.00544 46
		Organization (.30)	.00816 32
		Reporting Structure (.35)	.00680 40
		Size of Staff (.25)	.00680 41
		Nuclear Power (.50)	.03400 6
	Historical Performance (.40)	Current (.50)	.03400 7
		Fossil Power (.25)	.01700 13
		Current (.50)	.01700 14
		Industrial Work (.05)	.00340 54
		Current (.50)	.00340 55
		Size of Ave. Job (.20)	.01360 16
		Current (.50)	.01360 17

FIG. 9.—Management Capability Objective: Substructure

the evaluation, the decision maker must now accomplish a number of tasks. First, the decision maker must specify which, among the various criteria, are the most important, i.e., he must describe the scaling function,  $\pi_i$ . Second, the decision maker must determine to what degree various levels of performance,  $x_i$ , satisfy his preferences, and to what degree those preferences are modified in the presence of uncertain performance, i.e., he must describe the utility function,  $u(x_i)$ . The final task before the decision maker is to assign a range of potential performance for each performance criterion for each contractor, i.e., describe the probability density function,  $f(x_i)$ . Once these three tasks are accomplished and the requisite independence conditions are satisfied, the expected utility of each contractor's performance can be computed as follows:

$$EU(C_k) = \sum_{i=1}^{i=n} \int_{-\infty}^{\infty} \pi_i u(x_i) f(x_i)_k dx \dots \dots \dots (3)$$

in which  $EU(C_k)$  = the expected utility of Contractor  $k$ ;  $\pi_i$  = is the scaling function for objective (criterion)  $i$ ;  $u(x_i)$  = the utility function for objective

(criterion)  $i$ ; and  $f(x_i)_k$  = the probability density function for performance in objective  $i$ , given Contractor  $k$ .

**Assessing Utility Functions.**—Proper procedures for assessing the utility function,  $u(x_i)$ , are a matter of some controversy, and since the theoretical (and philosophical) aspects of quantifying risky choice "preferences" is somewhat beyond the scope of this paper, the interested reader is directed to Ref. 3. Likewise, precise interpretations of the scaling functions,  $\pi_i$ , and requirements for the additive representation are omitted and the interested reader is directed to Ref. 4. Henceforth, the existence of the  $n$  one-dimensional utility function for transforming contractor attributes into owner preferences and the scaling function,  $\omega_i$ , are assumed.

TABLE 2.—Summary Contractor Expected Utility Scores

Contractor (1)	Cost exposure objective (2)	Company stability objective (3)	Quality of product objective (4)	Management capability objective (5)	Total expected utility (6)
(a) Expected Utility Score					
A	0.322	0.027	0.043	0.190	0.582
B	0.355	0.019	0.054	0.198	0.626
C	0.371	0.034	0.053	0.255	0.713
D	0.377	0.033	0.049	0.195	0.654
(b) Utility Rank Order					
A	4	3	4	4	4
B	3	4	1	2	3
C	2	1	2	1	1
D	1	2	3	3	2

**Assessment or Risk.**—The third task before the decision maker, i.e., assessing the "riskiness" of each contractor's performance, requires some analysis. Each criterion was assumed to have a beta distribution which was specified by three estimates of potential contractor performance: (1)  $m$  = modal value of  $x$ ; (2)  $p$  = most pessimistic value of  $x$ ; and (3)  $o$  = most optimistic value of  $x$ . The mean and standard deviation of the beta distributions were estimated by

$$\mu = \frac{1}{6}(o + 4m + p); \quad \sigma = \frac{1}{6}(o - p) \quad \dots \dots \dots (4)$$

In order to present each contractor's performance on an attribute as a beta distribution, the decision maker must construct a measure to describe each contractor's optimistic, pessimistic, and modal performance values. To accomplish this evaluation, the decision maker must be clear in his own mind as to the source of risk in each of the performance attributes. In essence, there are two different elements of uncertainty in this evaluation. The first arises from possible variance in the scope of the work to be performed. The second is associated with the actual performance ability of the contractor.

## CALCULATING EXPECTED UTILITY AND RESULTS

Armed with this arsenal of utility curves, scaling functions, and probabilistic measures of contractor performance, the decision maker can now calculate the expected utility of each candidate contractor. The actual computations for this study were performed using a computer program called USEE2. USEE2 is a general purpose utility computation program which fits a piecewise curve to utility data and calculates appropriate probability density functions from  $\sigma$ ,  $m$ , and  $p$  estimates. USEE2 uses Simpson's rule to integrate the product of the probability density function and the utility function. This integration results in an expected utility  $EU(x_i)$  for each criteria. Each  $EU(x_i)$  is multiplied by the appropriate scaling function,  $\pi_i$ , and the products are summed to yield an overall measure of expected utility  $EU(C_k)$ . Detailed results of these utility computations are too lengthy for inclusion here; therefore the weighted utilities, summarized to the level of the higher level objectives, are presented in Table 2.

TABLE 3.—Comparison of Utility Analysis Results with Results of Traditional Analysis

Evaluation measure (1)	Ranking			
	First (2)	Second (3)	Third (4)	Fourth (5)
Total expected utility	C	D	B	A
Expected utility cost exposure objective	D	C	B	A
Traditional monetary evaluation	D	C	B	A

A number of pertinent observations can be drawn from Table 2. First, none of the contractors is clearly dominant in terms of meeting all of the owner's objectives. Each contractor, with the exception of Contractor A, received at least one first-place ranking. Comparing the two top-ranked contractors, i.e., C and D, in the two most heavily weighted objectives, shows that Contractor D is superior in cost exposure, while Contractor C is clearly superior in management capability. Second, Contractor C did not receive a ranking in any objective lower than second. Intuitively, this indicates that Contractor C presents a balanced, overall capability for pursuing this work. This, of course, is borne out by the overall ratings which indicate that Contractor C is indeed the highest-ranked contractor.

It is interesting to compare the results of this utility analysis with the results of the traditional monetary evaluation presented earlier. This is accomplished in Table 3.

It will be recalled that the traditional form of analysis included only the dollar-measured cost attributes. It must be noted that the cost exposure rank agrees identically with the traditional approach. Likewise, it is easily reasoned that the switch in relative positions of Contractor C and D occurs due to Contractor C's consistently higher ranking in the other noncost attributes.

## SUMMARY AND CONCLUSIONS

This paper has developed a contractor evaluation model which is appropriate in risky choice situations. The model is founded upon the value hierarchy

developed to represent the decision maker's preference in selecting a contractor. The utility model uses utility curves to represent the relationship between a specific capability of a contractor and the value of that capability in risky situations. The individual importance of each owner objective and each contractor attribute is specified using a weighting function which also incorporates the risk attitudes of the decision maker.

The utility model was used to rate four contractors in terms of their potential effectiveness. Contractor C was rated "best," primarily due to his promise of consistently good performance in regard to all owner objectives. The utility model results were insensitive to changes in the model data and parameters, and therefore provide a good degree of confidence in the final outcome.

Finally, this paper has attempted to demonstrate that it is possible to:

1. Formalize the cost-plus contractor selection process, and in doing so make it explicable, rational, and defensible.
2. Aid the decision maker in his task by making the underlying basis for his decision visible and quantitative.
3. Identify, catalogue, and assign priorities to decision objectives.
4. Determine and quantify relevant attributes of specific candidate contractors.
5. Aid the decision maker in communicating the structure of the decisions to his subordinates, peers, and supervisors.

In closing, a distinction needs to be made between good results and good decisions. Although no claim is made that use of this procedure will guarantee good results in terms of contractor performance, it is believed that application of a quantitative approach in complex and risky situations will aid an owner in making "good" decisions.

#### ACKNOWLEDGMENTS

The USEE2 Utility Analysis program was developed at Texas A & M University. The use of this program and the excellent advice concerning its use is gratefully acknowledged.

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## APPENDIX II.—NOTATION

*The following symbols are used in this paper:*

- $U(C_k)$  = overall measure of Contractor  $k$ 's utility score, indicating a combination of two or more  $u(x_i)$ ;  
 $u(x_i)$  = utility score, a risky measure of contractor performance,  $x_i$ , in terms of utility points;  
 $x_i$  = measure of contractor performance in its natural units; and  
 $\pi_i$  = utility weighting functions,  $\sum \pi_i = 1.0$ .



# JOURNAL OF THE TECHNICAL COUNCILS OF ASCE

## LNG TERMINAL DESIGN FOR CALIFORNIA<sup>a</sup>

By Thomas L. Anderson<sup>1</sup> and Robert E. Bachman,<sup>2</sup> Members, ASCE

(Reviewed by the Technical Council on Lifeline Earthquake Engineering)

### INTRODUCTION

A Liquefied Natural Gas (LNG) receiving terminal is under design for the coast of California as one of the projects to offset the state's declining supplies of natural gas. The baseload plant will receive gas volumes by tanker equivalent to about 25% of California's needs. Subsidiaries of Pacific Lighting Corporation and Pacific Gas and Electric Company have formed a partnership to develop the project. Safety of operation, covering not only safety within the plant boundaries but safety of the general public and of adjacent property, is a primary consideration in the design of this facility. Reliability of operation of the terminal upon which millions of users will be highly dependent, is also a primary consideration. These two design objectives, safety and reliability, are also the motivation for the emerging field of lifeline earthquake engineering (3).

To help ensure safety and reliability, extremely stringent seismic design criteria have been adopted for facility design. This is the first non-nuclear, nondefense project to be designed under such stringent criteria. This paper describes unique terminal design details, the design criteria, and their implementation, and design impact on major LNG terminal systems, with emphasis given to earthquake-related issues. It is hoped that the information presented in this paper will be of interest both to those who develop and those who implement design criteria for other important facilities which provide essential services to the public.

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## FACILITY LOCATION AND DESCRIPTION

The LNG receiving terminal will be located 130 miles (210 km) northwest of Los Angeles at a remote site near the foot of the Santa Ynez mountains on the Southern California coast approximately 3.5 miles (5.6 km) east of Point Conception at Little Cojo Bay (Fig. 1). The site occupies about 100 acres (40 ha) of coastal plain terrace which slopes downward to the south from the mountains at its northern boundary to coastal bluffs, which stand 50 ft–75 ft (15 m–23 m) above a narrow beach.

The major functions of the terminal are to offload, store, and vaporize the LNG. The vaporized gas is metered, odorized, and introduced via a new pipeline into an existing statewide pipeline system which supplies gas to over 6,000,000 customers throughout the state. Accordingly, the receiving terminal is an important link in California's natural gas lifeline system.



FIG. 1.—LNG Terminal Site Location

This current LNG import project will deliver through this terminal about 900,000,000 cu ft (standard)/day ( $25,000,000 \text{ m}^3/\text{day}$ ) (SCFD) of LNG from Indonesia and from the Cook Inlet area of Alaska. Eleven LNG carriers will be required to transport the LNG to the Little Cojo Bay Terminal. Final design engineering is scheduled to begin in 1981 with construction scheduled to begin in 1982. Provision is being made in the design to expand the ultimate capacity of the terminal to 1.3 billion SCFD ( $37 \times 10^6 \text{ m}^3$ ) baseload with an additional 0.3 billion SCFD ( $8.5 \times 10^6 \text{ m}^3$ ) load leveling.

Similar import projects have been operational throughout the world for a number of years. An LNG liquefaction plant in Alaska has been supplying

LNG to Japan for over a decade. France and England have been receiving LNG from Algeria since 1964. Italy and Spain receive LNG from Libya. In the United States, LNG has been imported since 1971 from Algeria to Everett, Mass. With two new large-scale terminals to handle Algerian gas recently opened at Cove Point, Md. and Savannah, Ga., the United States will commence major import programs. The Little Cojo Bay Terminal will be the first LNG baseload facility on the West Coast.

**Major Design Elements.**—A conceptual plot plan of the proposed facility is shown in Fig. 2. From a process viewpoint an LNG terminal is rather simple. The major operations are: (1) Unloading; (2) storage; (3) vapor handling; (4) vaporization; and (5) sendout.

The LNG is stored slightly above atmospheric pressure at a temperature of minus 260° F (−162° C) in insulated double walled metal tanks. The LNG is pumped out of the onshore LNG tanks using submerged internally mounted

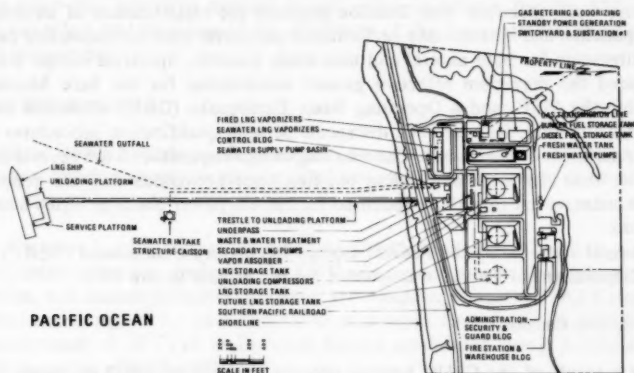


FIG. 2.—Facility Plot Plan (1 ft = 0.305 m)

pumps to secondary pumps which raise the liquid to sendout pressure. The LNG then enters the vaporizers where seawater is used as the heat source, with gas-fired vaporizers supplying peaking capacity. The seawater is pumped from an onshore basin to the falling film vaporizers and is then returned to the ocean.

#### DESIGN REQUIREMENTS

In 1973, a filing was made for a California LNG project with the former Federal Power Commission. Two terminal sites were proposed; one at Oxnard to receive Indonesian LNG, the other at Los Angeles Harbor (1) to receive Alaska LNG. With passage of the California LNG Terminal Act of 1977 (20), the original sites were ruled out by population density restrictions. The application was, therefore, amended in 1977 to a single terminal site at Little Cojo Bay (previously selected as the site for a future third project).

Over forty federal, state, and local agencies had either comment, review, or approval authority for this project. This was due to the lack of a single code, rule, or regulation for design and construction of LNG terminals and to the overlapping interests of various agencies.

The California LNG Terminal Act of 1977 directed the California Public Utilities Commission (CPUC) to approve a site and develop rules governing design, construction, and operation of such a terminal. The CPUC issued LNG Facilities Safety Standards (11) in mid 1979 in fulfillment of the Act. These safety regulations are hereafter referred to as GO 112-D.

As part of GO 112-D, the CPUC issued a set of design guidelines (7) to assist applicants in developing design criteria for LNG facilities. The guidelines principally address earthquakes, winds, tornadoes, and floods.

In its initial decision, July 1978, the CPUC issued a conditional permit for the construction and operation of an LNG terminal at Little Cojo Bay. In this decision (4) and in subsequent decisions (5) certain seismic and other design criteria were specified. The decision required the classification of structures, components, and systems into performance categories with corresponding design requirements for both natural and man-made hazards. Specified design criteria included the maximum effective ground acceleration for the Safe Shutdown Earthquake (SSE) and a Operating Basis Earthquake (OBE); allowable stress and load factors; fault setback distances; seismic qualification procedures and other pertinent requirements. The resulting design requirements are several times greater than the most demanding building code provisions and are generally more conservative than those specified for nuclear power plants in highly seismic regions.

Federal approval by the Federal Energy Regulatory Commission (FERC) and the Department of Energy was granted for the project in late 1979.

#### **SITE-SPECIFIC CRITERIA**

As a result of the CPUC hearing process, several technical decisions were made regarding specific criteria for the design of the Little Cojo Bay Terminal. These decisions included the definition of faults, the setback distances of structures from faults, the design accelerations for the site, and how these accelerations relate to response spectra.

**Fault Hazards.**—Two types of fault hazard are considered in the terminal design. Faults are used to establish vibratory design earthquake ground motions and to establish zones of possible surface fault rupture. For vibratory motion, faults within 60 miles (100 km) having historic or Quarternary displacement are considered. For establishing zones of possible surface rupture, onsite faults with activity within the past 100,000 yr–140,000 yr are considered.

If it is determined that a fault exists which has the potential for surface rupture at the site, the operator must demonstrate that safety-related structures can be either sited or designed to withstand the effects of anticipated surface rupture without functional impairment. If it is determined that safety-related structures must be sited to avoid the effects of surface rupture, the actual setback from the fault is established, on a case by case basis, after completion of a detailed site study of all earthquake-related geotechnical data. In no case may an LNG tank be sited within 100 ft (30 m) of a fault.

**Design Response Spectra.**—Three levels of seismic hazard are to be considered for design. These are SSE, OBE, and a UBC Earthquake (24). In general GO 112-D permits the SSE and OBE to be established on either a deterministic or probabilistic basis. However, as one of the conditions of approval of the Little Cojo Bay site, the CPUC mandated the SSE be defined as an earthquake of 7.5 Richter Magnitude occurring 3 miles (5 km) from the site. The CPUC further stipulated that this earthquake causes a "Design Maximum Acceleration" at the site of 0.70 g. The OBE is defined as one-half the SSE. The GO 112-D defines Design Maximum Acceleration as the maximum horizontal component of acceleration predicted to be effective at the ground surface and is used to scale design response spectra.

The SSE and OBE are defined in terms of response spectra. GO 112-D permits the facility to be designed using either the Regulatory Guide 1.60 (8) response spectra or the Newmark-Hall (17) response spectra. The Regulatory Guide 1.60 response spectra for horizontal motion have been selected for design at the Little Cojo Bay site. The vertical design response spectra for the SSE and OBE are taken as two-thirds of the amplitude of the horizontal design spectra at all frequencies.

#### SEISMIC SPECIFICATIONS

**General Design Criteria.**—All structures, components, and systems important to normal terminal operation are classified into one of the following three design categories:

1. Category I: All structures, components, and systems which perform a vital safety-related function, including the LNG storage containers, their impounding systems, and hazard protection systems, are classified Category I. All Category I items are designed for each natural or man-made hazard with a probability of occurrence of  $10^{-4}$ /yr or for each hazard established using deterministic methods as described by GO 112-D.
2. Category II: All structures, components, and systems not included in Category I which are required to maintain continued safe plant operation are classified Category II. All Category II items are designed for each natural or man-made hazard with a probability of occurrence of  $2 \times 10^{-3}$ /yr or for each hazard established using deterministic methods as described by GO 112-D.
3. Category III: All structures, components, and systems not included in Categories I and II, but which are essential for maintaining support of normal plant operations, are classified Category III. Category III items are designed in accordance with the provisions of the UBC, ANSI, API, or other applicable standards or codes.

The GO 112-D further requires that Category I items must be able to: (1) Perform their safety function without repair during and following the SSE; and (2) remain operational during and following the OBE. Category II items must be able to: (1) Operate without repair following the OBE; and (2) withstand the effects of the SSE without loss of structural integrity.

Generally, the governing seismic design load criteria for a given structure is dependent upon the category into which it is classified. However, it is acceptable

to support a structure, system, or component of a given category by a structure classified in a different category, provided it is demonstrated that the supported item can maintain its functional requirements specified by its design category. For these cases, the supporting structure would also be subjected to the seismic design loads of the supported item(s).

**Specifications.**—Specifications for designing and qualifying structures, systems, and components were drafted to implement the design criteria. This section describes how these specifications are utilized (see Fig. 3). The classification of all structures, components, and systems are contained in Specification A along with the specific design conditions the item must be designed to withstand. Seismic design spectra for individual items are contained in Specification B.

In Specification A all terminal facilities are assigned to one of two basic groups. The first group consists of structures, vessels, and piping systems. These are normally designed to meet allowable stress criteria and require specific

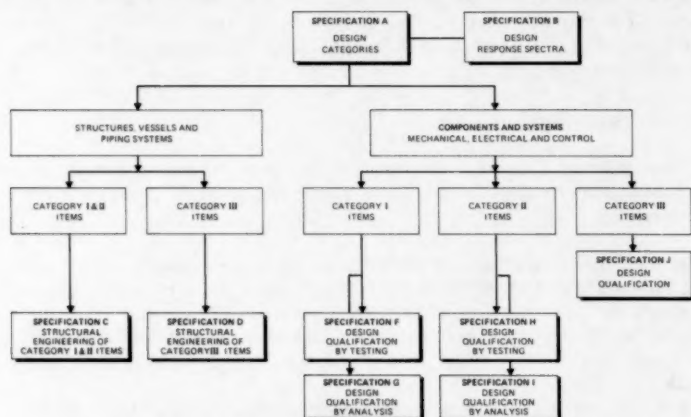


FIG. 3.—Specification Organization and Logic Diagram

analyses. For these items two detailed analytical specifications were developed (C and D). Specification C provides criteria for Category I and II items, and Specification D provides criteria for code-type static analysis.

The second group consists of mechanical, electrical, and control components and systems. These are normally qualified by testing or analysis methods. To simplify vendor communications, separate specifications (F, G, H, and I) were developed for both testing and analysis of Category I and II items. A separate specification was developed for Category III items. Thorough documentation of the qualification effort is required for third party review and audit.

**Load Combination, Load Factors, and Allowable Stresses.**—GO 112-D specifies load combinations and corresponding allowable stresses. These requirements are summarized for Working Stress design in Table 1 and for load factor design in Table 2. In general, no reduction in design forces to account for ductility is permitted. The only exceptions to this rule are for: (1) Category II items

subjected to SSE loads; and (2) structures which support items of a higher design category. For these cases a structure is allowed to experience some ductility during the higher level event, provided the structure maintains its structural integrity and such behavior does not impair the supported or adjacent item from performing its designated safety or operational function.

TABLE 1.—Working Stress Design

Design category (1)	Load combination (2)	Allowable stress for ductile elements (3)	Allowable stress for brittle elements (4) (5)	
All	$D + L$	$\sigma_n$	Normal code allowable	Normal code allowable
III	$D + L + E_{ubc}$	$1.33 \sigma_n$	Normal code allowable with normal code increase	Normal code allowable with normal code increase
I and II	$D + L + E_{obe}$	$1.33 \sigma_n$	$\sigma_{ut}/4^a$	$\sigma_{uc}/3^b$
I	$D + L + E_{ase}$	$1.5 \sigma_n^c$	$\sigma_{ut}/3^a$	$\sigma_{uc}/2^b$

<sup>a</sup>Tension.

<sup>b</sup>Compression.

<sup>c</sup>But not greater than 90% of yield stress.

TABLE 2.—Load Factor Design

Design category (1)	Load factor combination (2)
All	$U = 1.4D + 1.7L$
III	$U = 1.05D + 1.3L + 1.4E_{ubc}$
I and II	$U = 0.9D + 1.3L + 1.4E_{ubc}$
	$U = 1.05D + 1.3L + 1.4E_{obe}$
	$U = 0.9D + 1.3L + 1.4E_{obe}$
I	$U = 1.05D + 1.1L + 1.0E_{ase}$
	$U = 0.9D + 1.1L + 1.0E_{ase}$

Note:  $D$  = Dead load;  $L$  = live load;  $U$  = total load used to proportion element;  $E_{ubc}$  = UBC code load;  $E_{obe}$  = operating basis earthquake;  $E_{ase}$  = safe shutdown earthquake;  $\sigma_n$  = normal code allowable stress (for nonearthquake loads);  $\sigma_{ut}$  = ultimate strength in tension; and  $\sigma_{uc}$  = ultimate strength in compression.

**Comparison of LNG Seismic Criteria with Existing Codes.**—The seismic criteria outlined herein coupled with the site seismicity results in very conservative design loads. To provide a basis for comparison with other seismic codes, the effective design forces for four example structures have been calculated using these criteria and the seismic provisions of the UBC (24), ATC-3 (23), API 650 (26), and the United States Nuclear Regulatory Commission criteria as applied to the San Onofre Nuclear Power Plant (10). The four example structures consist

of three LNG terminal structures (LNG tanks, unloading dock and control building) and a hypothetical 10-story building. Characteristics for these structures assumed for evaluating the seismic design loads are given in Table 3 and the comparison is shown in Table 4.

TABLE 3.—Assumed Characteristics for Comparative Examples

Example (1)	Natural frequency, in hertz (2)	UBC (3)	ATC-3 (4)	GO 112-D (5)	USNRC San Onofre (6)
LNG tanks	9.0	$Z = 3/4$ ; $I = 1.5$ ; $C_p = 0.20$ ; $T_s = 0.5$ ; $\sigma_a = 1.33 \sigma_n$	$Z = 1.0$ ; $I = 1.5^a$ ; $C_1 = 0.24$ ; $\sigma_a = 1.67 \sigma_n$	Category I, $a_{psa} = 0.7 g$ ; 4.6% damping; $\sigma_a = 1.5 \sigma_n$	Category I, $a_{psa} = 0.67 g$ ; 4.6% damping; $\sigma_a = 1.6 \sigma_n$
Unloading dock	1.0	$Z = 3/4$ ; $I = 1.0$ ; $K = 1.33$ ; $T_s = 0.5$ ; $\sigma_a = 1.33 \sigma_n$	$A_v = 0.40$ ; $S = 1.0$ ; $R = 4.5$ ; $\sigma_a = 0.9$ $\times 1.7 \sigma_n$	Category II, $a_{psa} = 0.35 g$ ; 3.2% damping; $\sigma_a = 1.33 \sigma_n$	Noncategory I; same as UBC
Control building (box system)	7.0	$Z = 3/4$ ; $I = 1.5$ ; $K = 1.33$ ; $T_s = 0.5$ ; $\sigma_a = 1.33 \sigma_n$	$A_v = 0.40$ ; $S = 1.0$ ; $R = 4.5$ ; $\sigma_a = 0.9$ $\times 1.7 \sigma_n$	Category II, $a_{psa} = 0.35 g$ ; 5.8% damping; $\sigma_a = 1.33 \sigma_n$	Category I, $a_{psa} = 0.67 g$ ; 6.4% damping; $\sigma_a = 1.6 \sigma_n$
10-story steel braced frame bldg	1.3	$Z = 3/4$ ; $I = 1.0$ ; $K = 1.00$ ; $T_s = 0.5$ ; $\sigma_a = 1.33 \sigma_n$	$A_v = 0.40$ ; $S = 1.0$ ; $R = 5.0$ ; $\sigma_a = 0.9$ $\times 1.7 \sigma_n$	Category II, $a_{psa} = 0.35 g$ ; 3.2% damping; $\sigma_a = 1.33 \sigma_n$	Noncategory I; same as UBC

<sup>a</sup>See Reference 26.

TABLE 4.—Normalized Comparison of Net Seismic Design Forces: Ratio =  $[(F_p/\sigma_a) \text{ comparing criteria}] / [(F_p/\sigma_a) \text{ UBC}]$

Example (1)	UBC (2)	ATC-3 (3)	GO 112-D (4)	USNRC San Onofre (5)
LNG tanks	1.0	1.32 <sup>a</sup>	7.6	6.8
Unloading dock	1.0	1.17	7.7	Noncategory I same as UBC
Control building	1.0	1.61	4.2	6.5
10-story steel frame building	1.0	1.25	9.5	Noncategory I same as UBC

<sup>a</sup>See Reference 26.

Note:  $F_p$  = seismic base shear; and  $\sigma_a$  = allowable seismic design stress.

It is clear from Table 4 that the stringent seismic criteria for this project result in design forces which are in general an order of magnitude greater than required under the provisions of the UBC.

## SPECIAL DESIGN FEATURES AND CONSIDERATIONS

**LNG Storage Tanks.**—The LNG storage consists of 550,000 bbl (87,450 m<sup>3</sup>) double wall, suspended-deck type tanks designed to contain the liquid natural gas and to maintain it as a liquid with a minimum amount of boil-off vapor. The tanks are classified as design Category I. A conceptual design is shown in Fig. 4. The annular space between the inner 9% nickel steel tank and the outer carbon steel jacket is filled with loose perlite insulation. The 9% nickel steel was selected as the material for the inner tank because of its fracture toughness, high strength, and high ductility at cryogenic temperatures.

All process piping connections are through the tank roof; there are no penetrations of the tank wall or bottom. The tanks are maintained at 1 psig–2 psig (7 kPag–14 kPag) pressure. The pressure load is resisted by the outer tank.

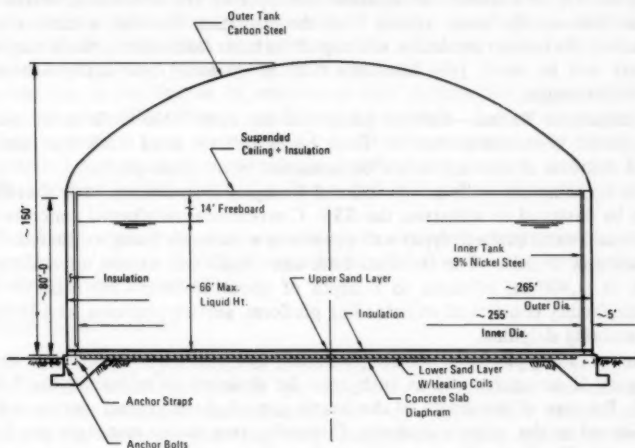


FIG. 4.—LNG Tank Cross Section: Conceptual (1 ft = 0.305 m)

Each tank will be supported by a continuous, reinforced concrete ring which also serves to anchor the stainless steel anchor straps of the inner tank and the steel anchor bolts of the outer tank. Cellular glass insulation blocks and a heated sand bed will prevent frost heave in the foundation.

Seismic analysis of the tanks will consider hydrodynamic forces. The impulsive contribution will be treated using the flexible tank approach developed by Veletsos and Yang (25). Convective forces and freeboard will be calculated using the Housner equations (12) with an added factor of 1.4 to correct for single direction motion used in the analysis. Damping of 1/8% will be used for convective effects based on observations of liquid filled containers reported by Deng (6) and Jacobsen and Ayre (14).

The design philosophy dictates the use of low aspect ratio, anchored tanks for the high seismic design levels postulated for the Little Cojo Bay site. Preliminary estimates indicate that the tank frequency will correspond to the

maximum amplified region of the response spectrum, reflecting a spectral acceleration of 1.9 g.

The tank wall thickness is governed by a combination of gravity loads, including hydrostatic effects, and horizontal and vertical seismic forces. Peak stresses occur in the circumferential direction at the vertical welds. Allowable stresses for the SSE load condition are set at 90% of the room temperature yield stress in the weld metal. The 60% increase in yield stress of the 9% nickel steel inner tank at cryogenic operating temperature is not permitted to be considered. The tanks will undergo hydro and pneumatic pressure testing. The hydrostatic testing will be done by filling the tank with water to the maximum design liquid level.

Interaction between the inner and outer tanks and potential slip of the inner tank base will be subjects of further studies. Preliminary work using nonlinear analysis (15) to simulate the dynamic behavior of the two tanks, interaction forces between the tanks arising from the insulation material, nonlinear compliance of the bottom insulation, and slip of the inner tank indicate these nonlinear effects will be small [slip less than 0.25 in. (6 mm)] and easily accounted for in the design.

**Containment Basins.**—Current plans call for each LNG tank to be placed in separate containment basins. Each basin will be sized such that the full liquid contents of the tank would be contained below plant grade.

The containment walls are considered Category I structures, and, therefore, must be designed to withstand the SSE. Conventional reinforced concrete and reinforced earth (tieback type) wall systems are currently being evaluated.

**Dock and Trestle.**—The terminal dock and trestle will extend approximately 4,600 ft (1,400 m) offshore to a depth of about 55 ft (17 m) MLLW. The marine facility consists of an unloading platform, service platform, and berthing and mooring dolphins.

The unloading platform, service platforms, and trestle are classified as design Category II structures and as such must be designed to withstand the 0.35 g OBE. Because of the length of the trestle, out-of-phase ground motion will be considered in the seismic analysis. Currently, two design concepts are being evaluated. The first utilizes steel pipe piles. The second concept utilizes a steel template structure below sea level and steel piles above sea level. In both concepts, the top of the pile groups are interconnected by moment resisting frames and the piles/jackets are grouted into drilled holes in the bedrock ocean floor.

**Seawater System.**—The seawater system consists of a caisson intake structure [located in about 35 ft (11 m) of water] connected by pipe to an onshore pump basin. Seawater flows by gravity through the intake structure to the onshore pump basin where it is pumped to the LNG vaporizers. The cooled seawater is discharged into the ocean through a discharge pipe extending about 4,300 ft (1,300 m) offshore.

The components of the seawater system are classified as Category II and, therefore, must be designed to withstand the 0.35 g OBE. Because of their length, the design of the intake and discharge lines will consider traveling earthquake wave effects. In addition, the caisson intake and discharge lines will be designed to withstand storm and tsunami wave loads.

**LNG Transfer System.**—The LNG Transfer System is designed to unload LNG at 40,000 gpm (2,500 L/s). In order to accommodate the large thermal

contractions, articulating joints are spaced along the LNG transfer system lines. Articulating joints (called gimbal joints) are installed to form a three-hinge mechanism. Current plans call for gimbal joint assemblies (three gimbal joints) on the unloading platform, and onshore near the trestle abutment. Each gimbal joint assembly will be designed to allow between 50 in. and 100 in. (1270 mm-2540 mm) of free thermal contraction. An additional allowance will be provided for out-of-phase seismic movement of the dock and trestle.

The LNG transfer system is classified design Category II. Because of nonuniform support motion experienced by the trestle and dock during a seismic event, the piping system and trestle will be analyzed together in one dynamic model. This combined model will permit seismic traveling wave effects to be treated directly in the analysis.

**Seismic Qualification of Equipment.**—Because of the requirement for safety and reliability of the LNG receiving terminal, seismic qualification of equipment will be an important effort. The method of seismic qualification, analysis or testing, will be preselected, as appropriate. In all cases, anchorage and leak tightness of equipment will be paramount concerns.

In addition to verification by analysis or test, documented prior application will be an acceptable seismic qualification approach. A growing number of equipment vendors have gained seismic qualification experience or established prequalified equipment through seismic qualifications programs for the Trans Alaska Pipeline Project, nuclear, military, defense, and electric utility applications.

The overall strategy to seismic qualification, including computerized records and tracking of seismic qualification progress, will follow the guidelines suggested by the writer and Nyman (2).

#### SUMMARY AND CONCLUSIONS

The LNG receiving terminal at Little Cojo Bay is seen as an important link in California's natural gas lifeline system. Safety and reliability concerns have led to remote siting and the imposition of very conservative seismic design requirements, which are generally more stringent than those applied to nuclear power plants.

Although LNG import programs have been in existence for many years, the restrictive seismic requirements applied to this terminal project make it unique. The special studies and design features incorporated to comply with the imposed standards are believed to reflect the most current seismic design philosophy for facilities which provide essential services to the public.

#### ACKNOWLEDGMENT

This paper is based on work done by the writers for Western LNG Terminal Associates. The opinions expressed herein are those of the writers and are not to be construed as representing the official position of Western LNG Terminal Associates or Fluor Engineers and Constructors, Inc.

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# JOURNAL OF THE TECHNICAL COUNCILS OF ASCE

## COMPUTER-AIDED ANALYSIS OF WATER RESOURCES SYSTEMS

By Clement Kleinstreuer<sup>1</sup>

(Reviewed by the Technical Council on Computer Practices)

### INTRODUCTION

Two major problem areas in the mathematical modeling of engineering systems are the: (1) Acquisition of reliable data sets; and (2) selection of the most appropriate solution technique, a problem of concern here. Computer simulation of large, or complex systems in hydrodynamics, or both, hydrology, water resources, ecology and related field requires, in general, a numerical solution method which should be stable, convergent, and computationally efficient. Any numerical scheme, in turn, requires a discretization of the system domain, i.e., the entire flow region has to be subdivided into neighboring finite elements (control volumes, cells, compartments, segments, etc.) in the form of a two- or three-dimensional mesh or grid. In addition, input data sets, such as environmental and operational conditions of the system, have to be prepared for the main program in order to run the computer simulation model once it is completed. A preprocessor called PREWARE (PREprocessor for WAtER REsources problems) was developed to solve in an automated interactive fashion the following "preliminary" tasks in the design of transport and conversion models:

1. Selection of the most suitable numerical method for solving large, or complex water resources problems, or both, depending on the system's characteristics and the project objectives.
2. Computer recognition of the system boundaries (shorelines, free surfaces, etc.) from United States Geological Survey maps or design drawings, as well

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as the automated generation of an appropriate mesh.

### 3. Preparation of all necessary data files for the source program.

An additional post-processing module has the capability of plotting the modeling results next to the mesh nodes, grid points, or compartment centers in terms of numbers (values of the principal variables), arrows (magnitude and direction of vector variables), or contours (isoparametric lines).

Preprocessors published in the open literature are either restricted to a particular numerical scheme, such as the finite element method, or were developed for elastostatic systems analysis only (3,7,12,15,18,23,24).

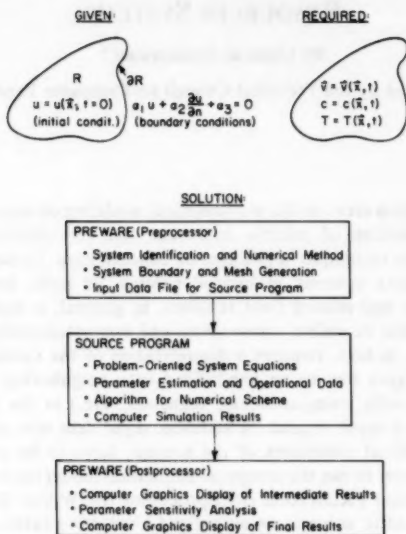


FIG. 1.—Uses of Preprocessor PREWARE

Engineering analysis and optimization techniques for water resources systems are well-documented in recent textbooks (2,4,16,21,26).

### NUMERICAL METHODS AND ASSOCIATED MESH GENERATORS FOR WATER RESOURCES PROBLEMS

The preprocessor PREWARE aids in the development of flow and constituent transport models, e.g., water movement in lakes, rivers, estuaries, and subsurface systems, as well as heat/mass transfer, toxic material uptake, and conversion in the aquatic environment (see Fig. 1). Thus, the geometrical boundaries are given or at least have to be assumed in studying, e.g., contaminated ground-water flow.

Numerical methods most frequently employed for solving water resources problems include the finite difference, the Galerkin finite element, the integrated finite volume approximation, and their spinoffs (1,5,6,8,10,13,14,21,27-30,32). Associated with each numerical scheme is a particular grid, mesh, or compartment network. *Finite difference methods* (FDM) are suitable for solving transient, multidimensional, nonlinear problems. Stability criteria are rather well-developed (19). The principal variables are evaluated at every grid point in the flow domain; thus the associated mesh generator produces a two- or three-dimensional grid thereby subdividing the system into rectangles or prisms (see Fig. 2).

The *Galerkin finite element method* (FEM) is very popular in subsurface hydrology and for flow regions with geometrically-complicated boundaries (see Fig. 3). Difficulties might be encountered in the analysis of time-dependent systems where inertial/advection terms have to be retained (17,22); stability criteria are not sufficiently developed yet. The associated mesh generator constructs, e.g., triangles in a two-dimensional, and triangular prisms in a three-dimensional case.

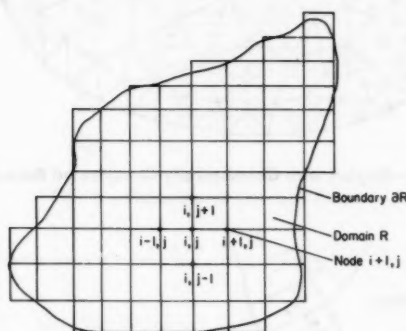


FIG. 2.—Grid Subdividing System into Rectangles or Prisms

The *integrated finite volume method* (IFVM) is rather simple and economical for modeling large flow systems where detailed (spatial) resolution is secondary. The associated mesh generator produces quadrilaterals or finite volumes (see Fig. 4).

#### DESCRIPTION OF PREPROCESSOR

The goal was to develop a preprocessor for water resources modeling which is a flexible, time- and cost-saving tool, and at the same time easy to use. PREWARE guides the user towards an optimal modeling approach by displaying: (1) The number and type of principal variables necessary to describe the dynamic state of the system; (2) the actual boundaries of the entire flow domain; (3) the expected results and relative costs in terms of computer storage and Central Processing Unit time; (4) the numerical scheme most suitable for the main program; (5) the associated mesh during all stages of development and interactive mesh

editing; (6) all necessary input data in a format acceptable to the source program; and (7) appropriate plotting methods for the final results. This is accomplished by interphasing the following subroutines (see Fig. 5):

1. *Systems analysis and model identification*, i.e., the most important features and influencing factors of water resources are conceptualized; questionnaires require system-characteristic information in terms of binomial answers on:

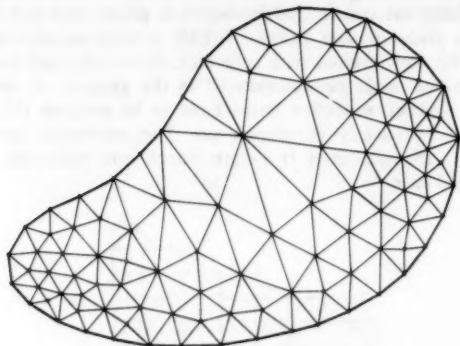


FIG. 3.—Region with Geometrically-Complicated Boundary

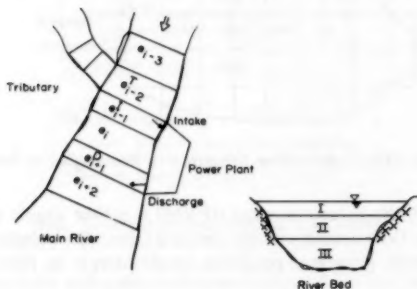


FIG. 4.—Volumes Produced by Associated Mesh Generator

site-specific geometric, process and environmental conditions, estimates of dimensionless groups, desired degree of resolution/accuracy, and other project objectives.

2. *Input modes for natural boundaries*, i.e., the scaled system domain is transformed and stored in the computer via the following input devices: (a) Batch mode using cards and pen/ink-type plotters; (b) keypunching of selected boundary points with subsequent curve fitting; (c) cursor/keyboard or light pens at graphics terminals; (d) separate tablets with electronic pens and data

processors; and (e) a combination thereof, depending on the availability of peripheral computer hard- and software (see Figs. 6 and 7).

3. *Interactive mesh generators*, i.e., the computer designs and element network based on the numerical method selected, the problem-specific geometry, and fluid flow patterns, as well as the user's specifications; mesh development can be constantly viewed on storage tube terminals or pen/ink plotters (see Figs. 8 and 9).

4. *Interface modules and data file preparations*, i.e., the cartesian coordinates

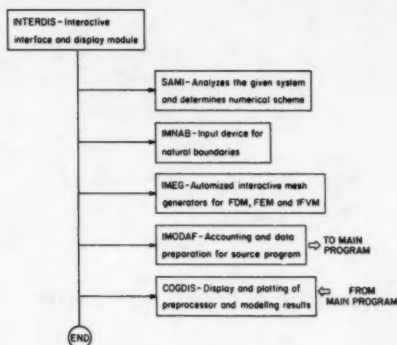


FIG. 5.—Functions of Solution Steps

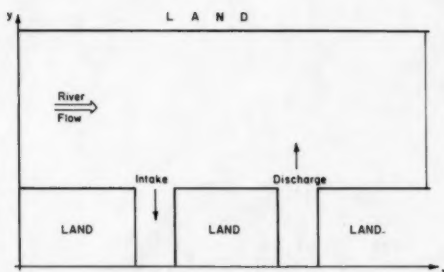


FIG. 6.—Input Mode for Natural Boundary

of all nodal points, prescribed boundary conditions, and the values of other model parameters are used to compute geometrical and operational data sets; interface modules put the prepared information into a format acceptable to the main program.

5. *Computer graphics display*, i.e., the user is interactively in visual feedback with the step-by-step output of every module of the preprocessor; final results of PREWARE and the computer simulation model are graphically displayed in various modes (see Fig. 10).

A detailed description of these subroutines, program listing, and documentation are given elsewhere (25).

**Sample Problem I.**—Consider a steam electric power plant located at a nontidal river. In order to investigate, in detail, the environmental impact of the operating plant, the hydrodynamics of the stream and the currents induced by cooling water pumps have to be investigated first. Based on the calculated velocity field in the vicinity of the plant, the thermal, chemical, and biological impact can be then evaluated.



FIG. 7.—Input Mode for Natural Boundary of Ohio River

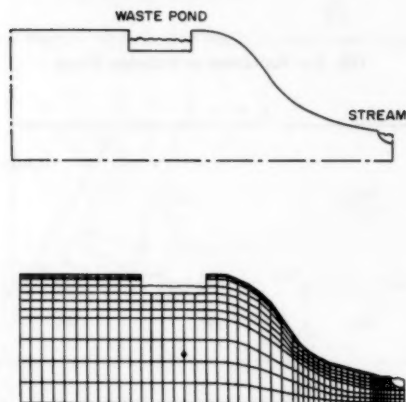


FIG. 8.—Mesh Development

**Solution Step 1.**—The module SAMI (Systems Analysis and Model Identification) asks the user questions pertinent to the system's characteristics, lower and upper bounds of the plant's operation, and the project's objectives. The interactive preliminary findings are the following:

1. The region of interest can be depicted as a straight river stretch with man-made intake and discharge canals (see Fig. 6).

2. The governing equations for the hydrodynamics of the problem:

$$\frac{\partial \bar{v}}{\partial t} + \nabla \cdot \bar{v} \bar{v} = \frac{1}{\rho} \nabla \cdot \bar{\pi} + \bar{f} \quad \dots \dots \dots (1)$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \bar{v}) = 0 \quad \dots \dots \dots (2)$$

can be reduced to:

$$\frac{\partial \bar{v}}{\partial t} + (\bar{v} \cdot \nabla) \bar{v} = \frac{1}{\rho} \nabla p + \nabla \cdot \nu' (\nabla \bar{v} + \nabla \bar{v}^T) + \bar{g} \quad \dots \dots \dots (3)$$

$$\nabla \cdot \bar{v} = 0 \quad \dots \dots \dots (4)$$

in which  $\bar{v} = \hat{i} u + \hat{j} v + \hat{k} w \triangleq$  velocity vector;  $\nabla \bar{v} =$  dyadic product,

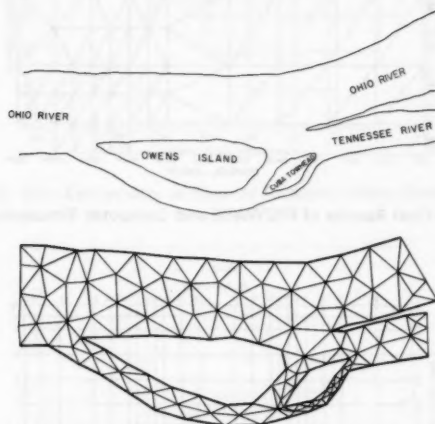


FIG. 9.—Mesh Development of Ohio River

and  $\nabla \bar{v}^T =$  its transpose;  $\bar{\pi} = p \bar{\delta} + \bar{\tau} \triangleq$  total stress tensor;  $\bar{f} \triangleq$  body forces;  $\rho \triangleq$  density;  $p \triangleq$  thermodynamic pressure;  $\bar{\delta} \triangleq$  unit tensor;  $\bar{\tau} \triangleq$  stress tensor;  $t \triangleq$  time;  $\nu' \triangleq$  turbulent kinematic viscosity (momentum diffusivity); and  $\bar{g} \triangleq$  effective gravitational force per unit mass (Boussinesq).

3. The finite difference method is recommended based on the simple geometry (see Fig. 6), the point-by-point resolution (distributed parameter approach) desired, and the fact that Eq. 3 could be further simplified (9,20) to a set of (scalar) *parabolic* equations.

**Solution Step 2.**—The module IMNAB (Input Modes for NATural Boundaries) has an easy task to store the straight shorelines (see Fig. 6).

**Solution Step 3.**—The module IMEG (Interactive MESH Generators) generates an appropriate finite difference grid (see Fig. 11). A higher line density is required

where steeper velocity gradients can be expected. Fig. 12 shows the bathymetry of the river at a particular cross section. A more elegant alternative solution of varying mesh density in two dimensions is given in Fig. 10.

**Solution Step 4.**—The module IMODAF (Interface Modules and Data File preparations) prepares data files for the main program. For example, the velocity vector at each boundary node along solid shorelines are set equal to zero, reflecting the "no slip" and the "no net flux" condition for impermeable

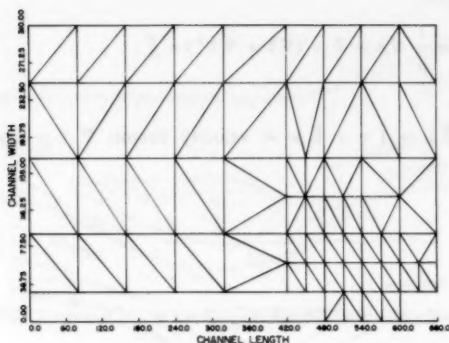


FIG. 10.—Final Results of PREWARE and Computer Simulation Model

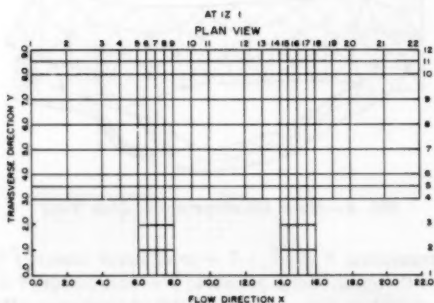


FIG. 11.—Finite Difference Grid Generated by IMEG Module

boundaries; to nodes on open-end boundaries, kinematic conditions, i.e., Neumann or Dirichlet type, are assigned; cross-sectional areas at any transect, volumes of river segments, the cartesian coordinates of each grid point etc., are put into appropriate files.

**Solution Step 5.**—The module COGDIS (Computer Graphics DISplay) was already employed for previous solution phases (Figs. 6–12). In a postprocessing mode, COGDIS generates a graphical representation of the final results of the

computer simulation model (see Fig. 13). Additional aspects of this problem are given in Ref. 11.

**Sample Problem II.**—Consider a continuation of sample problem I with the condition that the fate of constituent *c* (radionuclides, heat, toxic substances, passive biota, etc.), 100 miles downstream from the power plant should be investigated. Although the long river stretch is of arbitrary geometry, economical restrictions do not permit the development of a high resolution model.

**Solution Step 1.**—The subroutine SAMI recommends the IFVM, in which

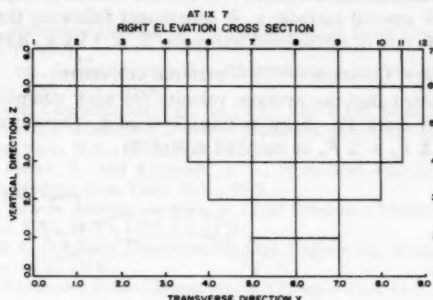


FIG. 12.—Bathymetry of River at Particular Cross Section

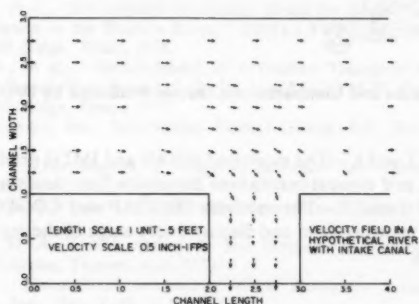


FIG. 13.—Final Results of Computer Simulation Model Generated by COGDIS Module

the flow domain is subdivided into completely mixed compartments (finite volumes), and the temporal change of principal variables is computed by summing up (integrating) all fluxes crossing the cell boundaries, plus all net productions within each cell. The generalized transport equation in integral form (21):

$$\left. \frac{DG}{Dt} \right|_{\text{system}} = \frac{\partial}{\partial t} \iiint_{c.v.} \rho \eta \, dV + \iint_{c.s.} \eta \rho \, \vec{v} \cdot d\vec{s} \dots \dots \dots (5)$$

takes on the form for constituent transport:

$$\dot{R}_i \pm \dot{S}_i = \frac{\partial}{\partial t} \iiint_{c.v.} c_i dV + \iint_{c.s.} c_i \bar{v} \cdot d\bar{s} \dots \dots \dots (6)$$

in which  $G_{\text{system}} = \iiint_{V_{\text{system}}} \rho y dV \hat{=}$  extensive system property, such as mass, momentum, energy, entropy, etc.;  $\eta = G$  per unit of mass  $\hat{=}$  intensive function (1,  $\bar{v}$ ,  $e$ ,  $s$ , etc.);  $\rho \hat{=}$  density of carrier fluid;  $\bar{v} \hat{=}$  velocity field, obtained from hydrodynamic considerations;  $c.v.$   $\hat{=}$  control volume (compartments, cells, segments);  $c.s.$   $\hat{=}$  control surface;  $c_i \hat{=}$  constituent following the fluid motion;  $\dot{R}_i \propto \iint_{c.s.} \bar{q}_D \cdot d\bar{s} \hat{=}$  rate of diffusional transport;  $\dot{S}_i \propto \iiint_{c.v.} q_S dV \hat{=}$  rate of net production;  $D/Dt \equiv (\partial/\partial t) + (\bar{v} \cdot \nabla) \hat{=}$  material derivative.

It has to be noted that the average velocity for each compartment or layer can be evaluated from Eq. 5 by setting  $G = m \cdot \bar{v}$ . Therefore,  $\eta \hat{=} \bar{v}$ , and  $DG/Dt|_{\text{system}} = \Sigma \bar{F}_S + \Sigma \bar{F}_B$  as outlined in Ref. 21.

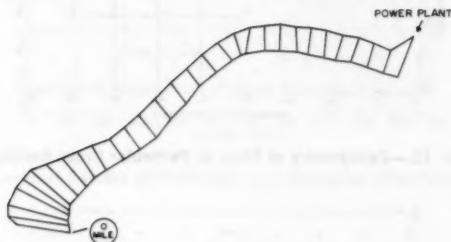


FIG. 14.—Boundaries and Compartmentalization Produced by IMODAF and COGDIS Modules

*Solution Steps 2 and 3.*—The modules IMNAB and IMEG produce the arbitrary river boundaries and compartmentalizes the entire flow domain (see Fig. 14).

*Solution Steps 4 and 5.*—The modules IMODAF and COGDIS prepare input data files for the main program and display every stage of the model development in graphical form.

## CONCLUSIONS

It was indicated that a generalized preprocessor for numerical fluid flow and constituent transport models can be a helpful, cost-effective research tool contributing significantly to the accurate analysis and modeling of large, or complex systems, or both. This preprocessor, called PREWARE, could be expanded to include: a wider range of numerical schemes to choose from, higher-order element interpolation functions, and an extended number of finite element mesh generators. However, there is a certain "danger" that a simple and flexible tool becomes so complex that only a few researchers can use it after all "additions" are incorporated.

Future work will concentrate on the development of a self-adjusting *dynamic*

network program which changes the size, density, and smoothness of the (finite) elements according to gradients of the principal variables calculated in *previous* trial runs until an optimal global mesh is adapted for a particular numerical scheme. This advancement would be important since the right mesh selection is crucial for the stability, accuracy, and efficiency of all numerical methods (31).

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## APPENDIX II.—NOTATION

*The following symbols are used in this paper:*

- $c$  = constituent concentration;
- $e$  = specific energy;
- $\bar{F}_b$  = body forces;
- $\bar{F}_s$  = surface forces;
- $\bar{f}$  = specific forces;
- $G$  = arbitrary, extensive system property;
- $\bar{g}$  = effective gravitational force per unit mass;
- $\hat{i}, \hat{j}, \hat{k}$  = cartesian unit vectors;
- $p$  = pressure;
- $\bar{q}_D$  = heat or material flux;
- $q_s$  = source/sink, net production per unit volume;
- $\bar{R}$  = diffusional transport term;
- $\dot{S}$  = net sinks and sources;
- $\bar{s}, s$  = surface area of control volume, specific entropy;
- $t$  = time;
- $u, v, w$  = cartesian velocity components;
- $\bar{v}$  = velocity field;
- $\bar{\delta}$  = unit tensor;
- $\eta$  = intensive system function;

- $\nu'$  = turbulent kinematic viscosity;  
 $\bar{\pi}$  = total stress tensor;  
 $\rho$  = density;  
 $\bar{\tau}$  = stress tensor; and  
 $\nabla = \hat{i}(\partial/\partial x) + \hat{j}(\partial/\partial y) + \hat{k}(\partial/\partial z)$  = del operator;  $\nabla \cdot \bar{v} = \text{div } \bar{v}$ .

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# JOURNAL OF THE TECHNICAL COUNCILS OF ASCE

## LONG TIME OBSERVATION OF A FATIGUE DAMAGED BRIDGE<sup>a</sup>

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Hans Hausammann,<sup>3</sup> and Alan W. Pense<sup>4</sup>

(Reviewed by the Technical Council on Research)

### INTRODUCTION

Fatigue cracking was first observed at the Yellow Mill Pond Bridge on the Connecticut Turnpike (Interstate Route 95) in 1970. Fatigue crack growth had resulted in complete fracture of a tension flange. Inspection of two beams adjacent to the fractured beam indicated fatigue cracks had propagated halfway through their tension flange. Also, small cracks were visually observed (10× magnification) at several other beams. Nondestructive verification could not always be obtained for these smaller cracks using ultrasonic methods, dye penetrant, or magnetic particle inspection procedures. A reexamination in 1973 provided confirmation that a crack existed at one cover plate detail. In 1976 a detailed inspection was conducted of the beams in the eastbound and westbound span 10 bridges. Follow-up inspections were carried out in November 1977 and November 1979.

The possibility of fatigue cracking at cover-plated beam details was clearly demonstrated by the American Association of State Highway Officials (AASHO) Road Test (13). In this test cracking occurred at relatively high service stress ranges. Laboratory fatigue tests with constant amplitude loading have been used to define the design fatigue strengths of a wide range of details including cover-plated beams (7). Tests have also been undertaken on comparable small

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scale cover-plated beams under random variable loading (11). In addition, full-scale beams were tested to determine their fatigue and fracture resistance (8,10). Therefore, available laboratory data and actual field data on the cyclic stresses and the observed cracking of full-scale bridge members provide a unique opportunity to define the high cycle fatigue resistance of the full-scale cover-plated beams.

The Yellow Mill Pond Bridge is located on the Connecticut Turnpike (Interstate Route 95) in the City of Bridgeport, Conn. Construction started in 1956 and was completed in 1957. It was opened to traffic January 1958. This bridge complex consists of 28 simple-span cover-plated steel beam bridges crossing the Yellow Mill Pond Channel (14 in each direction of traffic). Each bridge carries three lanes of traffic. The position of the beams and diaphragms in span 10 are shown in Fig. 1. The external fascia beam (beam 1) of the eastbound bridge is skewed as four lanes of through traffic are being reduced to three lanes. Both roadways were designed as composite sections for HS20 loading (2).

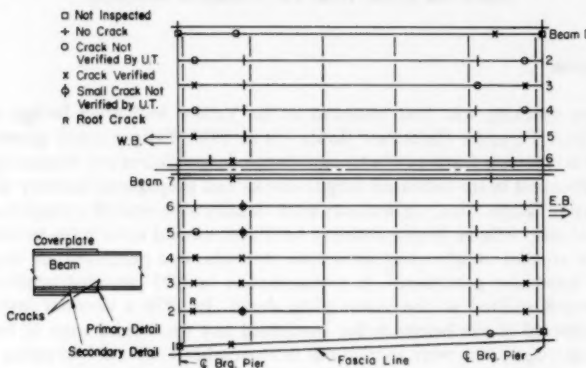


FIG. 1.—Plan Showing Inspected Details in Span 10

The beams in span 10 are W36  $\times$  230, W36  $\times$  280, or W36  $\times$  300 sections and were rolled from A242 steel. All beams, except the interior fascia beam of the eastbound roadway (beam 7), are fitted with two cover plates (primary and secondary) on the tension flange and a single cover plate on the compression flange. The primary cover plates for the exterior fascia beams of both roadways are full length.

The cover plate ends are not tapered. The corners are rounded to a radius of 3 in. (76 mm). Measurements of the fillet welds at the cover plate ends in the field confirmed a weld leg size between 0.5 in.–0.6 in. (13 mm–15 mm). Figure 2 shows a typical cover plate and weld detail and a fatigue crack at the weld toe. End welds connecting a cover plate to a rolled section were classified as primary details. End welds connecting the second cover plate to a primary cover plate were classified as secondary details. Both bridges of span 10 have 7.25 in. (184 mm) reinforced concrete decks.

This paper examines the reasons for the cracking that developed in these



FIG. 2.—Cover Plate End Showing Fatigue Crack at Weld Toe

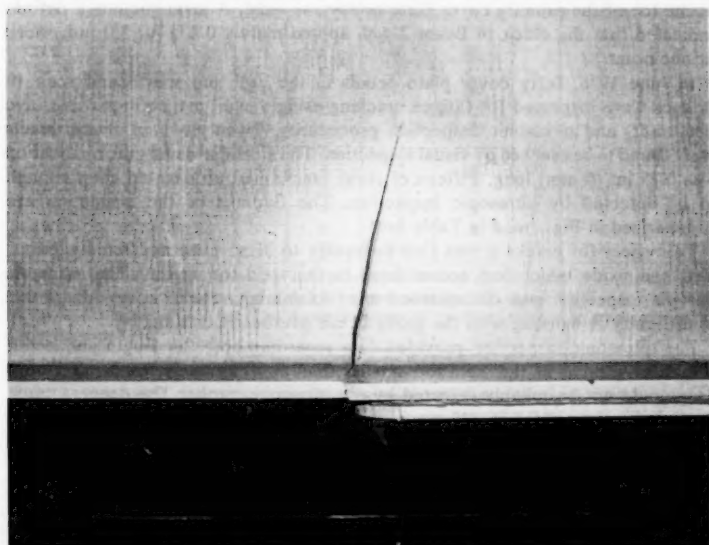


FIG. 3.—Fractured Girder Discovered in 1970

bridge structures and its relationship to the laboratory test data. It demonstrates the need for experimentally assessing the fatigue resistance of welded details.

#### REVIEW OF INSPECTION AND STRESS HISTORY MEASUREMENTS

**Nondestructive Crack Inspection.**—In October–November, 1970, during cleaning and repainting of the Yellow Mill Pond Bridge, one of the cover-plated steel beams on the eastbound bridge on span 11 was found to have a large crack (2). The crack had developed at the west end of the primary cover plate on Beam 4 and is shown in Fig. 3. It had grown from the toe of the cover plate transverse fillet weld into the tension flange and up 16 in. (400 mm) into the web.

A visual inspection (10× magnification) showed that Beam 3 and Beam 5 in span 11 of the eastbound roadway which were adjacent to the casualty girder had cracks along the cover plate ends. These cracks were subsequently verified by ultrasonic testing and a depth of penetration equal to 0.625 in. (16 mm) was measured. An indication of possible fatigue cracking was also observed at other details on span 10 and on span 11.

In December 1970, after the detailed inspection, a section of the fractured girder was removed and all three damaged girders were subsequently repaired with bolted web and flange splices. An indication of possible cracking was also observed at Beam 3 in 1970. In November 1973, the east ends of Beams 2 and 3 in the eastbound roadway of span 10 were inspected again by the first writer for fatigue damage. Cracks were detected visually in both girders at the toe of the primary cover plate transverse weld. A magnetic crack definer indicated that the crack in Beam 2 was approximately 0.275 in. (10 mm) deep at one point.

In June 1976, forty cover plate details in the east and westbound span 10 bridges were inspected for fatigue cracking using visual, magnetic particle, dye penetrant, and ultrasonic inspection procedures. Twenty-two of these details were found to be cracked by visual inspection. The smallest visual crack indication was 0.25 in. (6 mm) long. Fifteen of these cracks had propagated deep enough to be detected by ultrasonic inspection. The findings of the inspection are summarized in Fig. 1 and in Table 1.

To inspect for cracks it was first necessary to blast clean and remove paint, dirt, and oxide which had accumulated in the weld toe region. The magnetic particle inspection was discontinued after examining several cover plates due to difficulty in working with the probe in the overhead position.

The ultrasonic inspection provided data regarding both the length and depth of cracks. Cracks at the weld toe smaller than approximately 0.1 in. (2.5 mm) deep could not be reliably detected by the ultrasonic probe. The deepest crack depth indications of 0.5 in. (13 mm) were found at the west end of the eastbound span 10 bridge in Beam 3 and Beam 7. Comparisons of estimated crack depths from ultrasonic inspection and actual measured crack depths after a fracture surface was exposed indicate that deviations of  $\pm 0.063$  in. (1.6 mm) are possible (8). The crack inspection history for span 10 is summarized in Table 1.

In November 1976, a brief inspection was made by the first writer at span 13. Four large cracks were detected without removing the paint. These cracks were first observed with field glasses from the ground. It is believed that these

cracks must be approximately 6 in.-10 in. (150 mm-250 mm) long and about 0.5 in. (13 mm) deep for the crack to break the paint film at the weld toe. Decreasing temperatures cause a more brittle paint coat and increase the likelihood of the paint to crack.

In September 1977 an inspection was made by the first writer at span 10. The secondary details at Beam 5 of the westbound bridge and the secondary details of Beam 5 and Beam 6 of the eastbound bridge at the east end were

TABLE 1.—Inspection History (Span 10)

Detail (1)	Eastbound						Westbound		
	Decem- ber 1970 (2)	Novem- ber 1973 (3)	June 1976 (4)	Novem- ber 1976 (5)	Septem- ber 1977 (6)	Novem- ber 1979 (7)	June 1976 (8)	Septem- ber 1977 (9)	Novem- ber 1979 (10)
1ES	X	X	C	X	X	C	CV	X	CV
2EP	X	CV	CV	X	X	NC	C	X	C
2ES	X	X	NC	X	X	X	NC	X	X
3EP	C	C	CV	X	X	C	CV	X	CV
3ES	X	X	NC	X	X	X	CV	X	X
4EP	C	X	CV	X	X	X	C	X	CV
4ES	X	X	NC	X	X	X	NC	X	X
5EP	NC	X	NC	X	X	X	NC	X	X
5ES	X	X	X	X	X	X	X	X	X
6EP	X	X	NC	X	X	X	NC	X	X
6ES	X	X	X	X	X	X	NC	X	X
7EP	X	X	NC	X	X	X	NA	X	X
1WS	X	X	CV	X	C	CV	CV	X	X
2WP	X	X	CV	X	X	R	C	X	X
2WS	X	X	NC	X	X	C	NC	X	X
3WP	C	X	CV	X	NC	CV	CV	X	X
3WS	X	X	CV	X	C	C	NC	X	X
4WP	C	X	CV	X	X	NC	C	X	X
4WS	X	X	NC	X	C	CV	NC	X	X
5WP	C	X	C	X	C	NC	CV	X	X
5WS	X	X	NC	X	X	X	X	X	X
6WP	X	X	NC	X	X	X	X	X	X
6WS	X	X	NC	X	NC	X	CV	C	X
7WP	X	X	CV	X	NC	CV	NA	X	X

Note: # = beam number; E = east end of beam; W = west end of beam; P = primary cover plate detail; S = secondary cover plate detail; NA = not applicable; R = root crack; X = no inspection; NC = no indication of cracking; C = visual indication of cracking; and CV = crack verified by ultrasonic inspection.

inspected for the first time. No cracks were found. However, small cracks were found at the secondary detail of Beam 4, Beam 5, and Beam 6 of the eastbound bridge at the west end. These details had been inspected in 1976, but no cracks were found. In addition, some cracks were found in details on span 12. The cracks were up to 15 in. (381 mm) long.

In November 1979 an inspection (visual and ultrasonic) of some details in span 10 was made. Ultrasonic testing verified the existence of the crack found in the 1977 inspection at the secondary detail of Beam 4 of the eastbound structure at the west end. The retrofitted details were also examined and a

crack growing from the root was found in Beam 2 at the primary detail of the eastbound bridge at the west end (see Fig. 4). This was the only root crack detected. The crack was 1.25 in. (32 mm) long on the surface (verified by dye penetrant) and 6 in. (152 mm) long at the root (measured with the ultrasonic

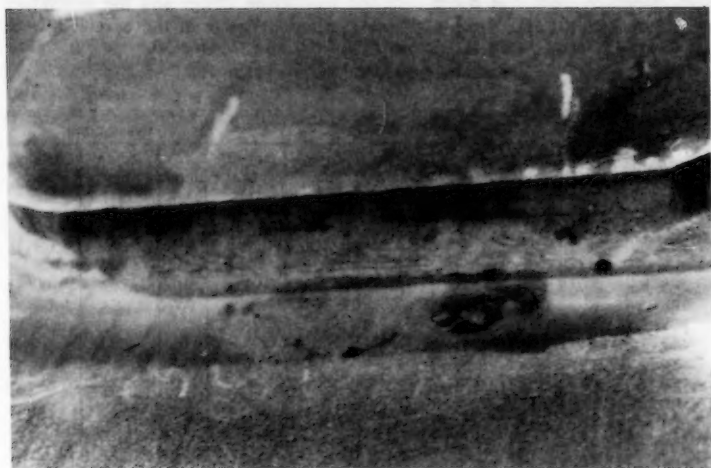


FIG. 4.—Root Crack in Cover Plate End Weld

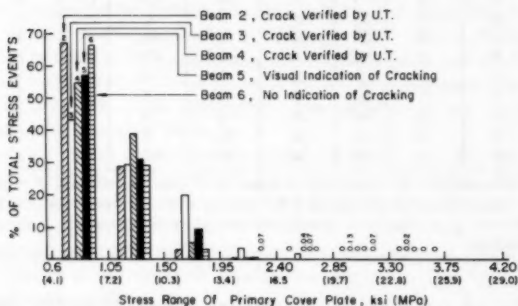


FIG. 5.—Stress Range Histogram: West Ends of Eastbound Span 10 (1971)

probe). The crack had penetrated the full width of the cover plate. Small cracks were also found for the first time at the secondary detail of Beam 2 of the eastbound bridge at the west end.

**Stress History Studies.**—The eastbound and westbound bridges of span 10 in the Yellow Mill Pond viaduct were selected for the test spans in two major

stress history studies. Both studies were conducted by the State of Connecticut and the Federal Highway Administration. The first study was conducted in July 1971 (2) and the second from April 1973–April 1974 (4).

In the July 1971 study electrical-resistance strain gages were placed at two principal locations on each of the interior beams. One gage was placed at midspan

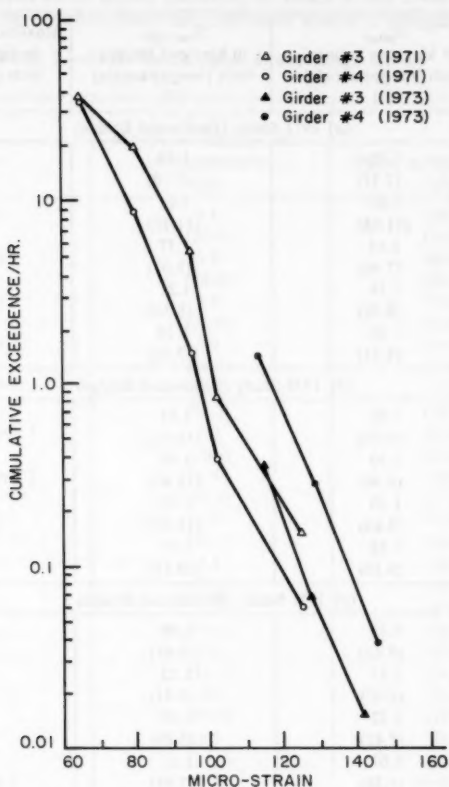


FIG. 6.—Distribution of Strain in Eastbound Beams 3 and 4 (1971 and 1973)

and the other gage was placed 4 in. (102 mm) from the end of the primary cover plate. All of the strain gages were placed directly under the web on either the flange or primary cover plate.

A typical stress histogram for the gage on the girder of the eastbound lanes is shown in Fig. 5. Truck distribution and lane counts were also conducted concurrently with the collection of stress history data on span 10. Truck weights were sampled 9.25 miles (14.8 km), ten exits, west of the test span at a rest area near Westport (2).

From April 1973–April 1974 the stress history for the eastbound bridge of span 10 was monitored by mechanical strain recorders (4). These instruments measure total deformation over the recorder gage length [approximately 36 in.

TABLE 2.—Stress Ranges at Weld Toe (Span 10)

Detail (1)	$S_{RMS}$ , in kips per square inch (megapascals) (2)	$S_{MINER}$ , in kips per square inch (megapascals) (3)	Maximum stress range, in kips per square inch (megapascals) (4)
(a) 1971 Study (Eastbound Bridge)			
2WP	1.06 (7.31)	1.10 (7.58)	2.40 (16.55)
3WP	1.60 (11.03)	1.61 (11.10)	3.75 (25.85)
4WP	1.14 (7.86)	1.17 (8.07)	2.85 (19.65)
5WP	1.16 (8.00)	1.21 (8.34)	2.85 (19.65)
6WP	1.06 (7.31)	1.10 (7.58)	3.30 (22.75)
(b) 1976 Study (Eastbound Bridge)			
3WP	1.41 (9.72)	1.67 (11.51)	>6.00 (>41.36)
7WP	1.30 (8.96)	1.98 (13.65)	>6.00 (>41.36)
2EP	1.40 (9.65)	1.95 (13.44)	>6.00 (>41.36)
3EP	1.32 (9.10)	1.47 (10.14)	3.61 (24.82)
(c) 1971 Study (Westbound Bridge)			
2EP	1.37 (9.45)	1.46 (10.07)	4.20 (28.95)
3EP	1.17 (8.07)	1.22 (8.41)	4.20 (28.95)
4EP	1.22 (8.41)	1.29 (8.89)	4.20 (28.95)
5EP	1.07 (7.38)	1.11 (7.65)	3.00 (20.68)
1ES	1.60 (11.03)	1.77 (12.20)	6.00 (41.36)
3ES	1.48 (10.20)	1.58 (10.89)	3.60 (24.82)

(914 mm)] which is attached to the beam. The strain cycles are recorded on a data disk which advances after each event.

A mechanical strain recorder was attached at midspan to Beam 3 and Beam 4. For a two-week period electrical strain gages were also sampled at midspan for Beam 3 and Beam 4. During this period transfer functions were developed

that related the data recorded simultaneously by the electrical strain gages to the average strains over the gage length recorded by the mechanical strain gages.

The mechanical strain recorders continued to collect data from July 1973–April 1974. The minimum recorded average strain was approximately 60  $\mu\text{in./in.}$  Corrosion and sticking occurred with many of the data disks. Based upon approximately 3,400 hr of usable recording at Beam 3 and 5,400 hr at Beam 4, and using the transfer functions, the equivalent strains at midspan are plotted

TABLE 3.—Cover-Plated Beam Stress Range Survey

Bridge (1)	$S_{\text{max}}$ in kips per square inch (megapascals) (2)	Span, in feet (meters) (3)
Michigan 1	5.1 (35.2)	79.5 (24.2)
Michigan 2	5.6 (38.6)	66.0 (20.1)
Michigan 3	4.5 (31.0)	71.9 (21.9)
Michigan 4	3.9 (26.9)	58.7 (17.9)
Michigan 5	5.1 (35.2)	78.5 (23.9)
Pennsylvania 1	3.0 (20.7)	62.3 (19.0)
Pennsylvania 2	1.5 (10.3)	49.7 (15.1)
Alabama 1	7.3 (50.3)	80.0 (24.4)
Alabama 2	5.3 (36.5)	55.0 (16.8)
Alabama 3	7.3 (50.3)	80.5 (24.5)
Maryland 1	1.9 (13.1)	47.0 (14.3)
Maryland 2	4.4 (30.3)	41.9 (12.8)
Virginia 1	3.5 (24.1)	74.5 (22.7)
Minnesota 1	3.8 (26.2)	38–61–38 (11.6–18.6–11.6)

in Fig. 6 (1973) and compared with strains recorded at midspan for Beam 3 and Beam 4 during the July 1971 study. The minimum mechanical recorder average strain (approximately 60  $\mu\text{in./in.}$ ) when corrected by the transfer function results in a midspan strain of approximately 110  $\mu\text{in./in.}$  Figure 6 suggests that slightly higher stress range events did occur over the extended time period in 1973, than measured during the 1971 study.

A limited strain history record was obtained for the eastbound bridge of span 10 in June 1976. Electrical-resistance strain gages were mounted on the

east end of Beam 2 and Beam 3 and on the west end of Beam 3 and Beam 7, respectively. All the gages were placed on the tension flanges of the rolled beams directly under the web and 2 in. (50.8 mm) off the end of the cover plate.

A large stress event was recorded during the stress history sample of the west end of the eastbound bridge. Inspection of the oscillograph trace indicated that this stress event was caused by a multiple truck presence on the bridge. The stress range recorded at the end of the cover plate was 10.5 ksi (72.4 MPa) for Beam 7 and the strain trace ran off the recording paper at a stress of 7.2 ksi (49.6 MPa) for Beam 3. The earlier studies indicated that stresses of this magnitude would not be common. Miner and root-mean-square (RMS) stress values, based on the frequency and magnitude of strain events recorded in the July 1971 study and the 1976 sample were calculated. The following equations were used to calculate these values:

$$S_{\text{RMS}} = (\alpha_i S_i^2)^{1/2} \quad \dots \dots \dots (1)$$

$$S_{\text{RMINER}} = (\alpha_i S_i^3)^{1/3} \quad \dots \dots \dots (2)$$

in which  $S_i$  = the  $i$ th stress range in the spectrum; and  $\alpha_i$  = the fraction of stress ranges of that magnitude. The stress ranges are shown in Table 2.

The Miner and root-mean-square stress ranges for the July 1971 study do not differ as much as implied by the June 1976 sample. This is partially attributable to the large stress range events recorded in the 1976 sample. Comparing the results of both studies where the minimum recorded stress range was 0.6 ksi (4.14 MPa), the RMS stress range was 13% higher and the Miner stress range was 3% lower in 1971 than in 1976 (see Table 2).

The live load stress histograms obtained at Yellow Mill Pond are similar to the stress histograms that have been obtained at other cover-plated beam bridges in Michigan, Virginia, Maryland, Tennessee, and Pennsylvania (see Table 3). The highest measured stress range varied from one histogram to another, but the vast majority of these studies indicate an effective (Miner or RMS) stress range between 1.0 ksi (6.9 MPa) and 2.0 ksi (13.8 MPa). Also, the frequency distribution curve is concave from the modal stress range to the highest measured stress range. The highest measured stress ranges varied between 1.5 ksi (10.3 MPa) and 6.9 ksi (47.6 MPa) which is directly comparable to the observations at Yellow Mill Pond.

#### LABORATORY TESTS ON COVER-PLATED BEAMS

Laboratory studies have been carried out at Lehigh University to establish the high cycle fatigue strength of welded bridge details. One project involved the testing of small-scale cover-plated beams (W14  $\times$  30). The American Association of State Highway and Transportation Officials (AASHTO) specification provisions for cover-plated beams (Category E) were based on the results of these tests. Tests have also been undertaken at the United States Steel Corporation on similar cover-plated beams under random variable loading (11). Several full-scale beams were also tested at Lehigh to determine their fatigue and fracture resistance.

**Constant-Amplitude Tests.**—Twenty-five end-welded cover-plated beams (W14

$\times 30$ ) were tested at stress ranges between 4 ksi (27.6 MPa) and 8 ksi (55.2 MPa) (5). Five beams were cycled to 100,000,000 cycles without detecting fatigue cracking. The lowest stress range at which fatigue failure was observed was 4.7 ksi (32.4 MPa). The results of all constant-cycle fatigue tests at a stress range of 6 ksi (41.4 MPa) or less are plotted in Fig. 7.

The beam failures generally fall within the extension of the 95% confidence limits of the mean regression line for all end weld cover plate failures reported

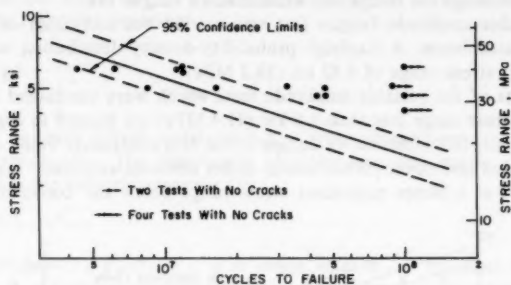


FIG. 7.—Small Scale Beam Constant-Amplitude Fatigue Strength

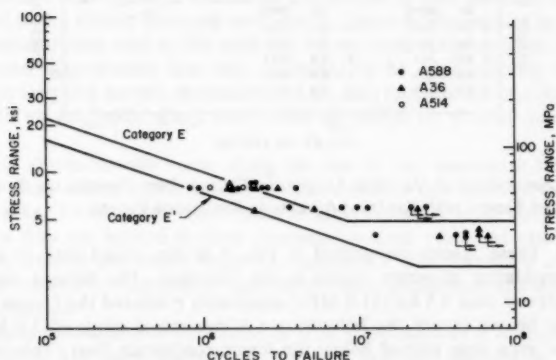


FIG. 8.—Fatigue Strength of Full Size Cover-Plated Beams

in National Cooperative Highway Research Program (NCHRP) Report 102 (5). The 95% confidence limits in Fig. 7 are approximated as twice the standard error of estimate on each side of the mean regression line. Twenty full size cover-plated beams ( $W36 \times 230$  or  $W36 \times 260$ ) were tested under stress ranges between 4.0 ksi (27.6 MPa) and 8.0 ksi (55.2 MPa) (8,10). The beams were the same size as many beams at the Yellow Mill Pond. The test data for cover plate details with flange thickness greater than 1.25 in. (32 mm) yielded a fatigue

strength less than Category E (8). This has resulted in defining a lower bound fatigue Category E', which is applicable to cover-plated beams with a flange thickness greater than 0.8 in. (20 mm). The test results are shown in Fig. 8.

**Variable-Amplitude Tests.**—Twelve end-welded cover-plated beams, W14  $\times$  30, were tested at an equivalent Miner stress range less than 6.0 ksi (41.4 MPa) (11). The variable-amplitude stress range distribution used in this study satisfied a Rayleigh probability-density curve. When testing was discontinued, all of the cover plate welds were cracked, but three of the cracks had not propagated completely through the flange and exhausted all fatigue life.

One variable-amplitude fatigue test was carried out at Lehigh on a W12  $\times$  36 cover-plated beam. A Rayleigh probability-density distribution was applied with a Miner stress range of 4.82 ksi (33.2 MPa).

The results of the variable-amplitude tests which were conducted at a Miner equivalent stress range less than 6.0 ksi (41.4 MPa) are plotted in Fig. 9. These results generally fall within the extension of the 95% confidence limits determined for end-welded and cover-plated beams under constant-amplitude loading. Two beams failed at a Miner equivalent stress range below the constant-amplitude

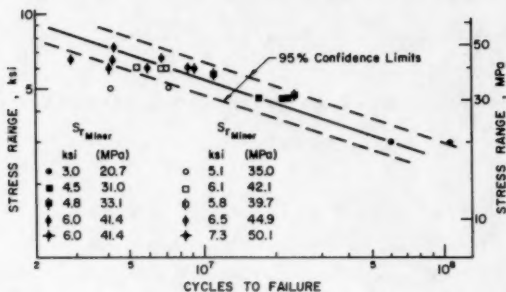


FIG. 9.—Comparison of Variable Amplitude Fatigue Test Results on Small Scale Cover-Plated Beams with Constant Amplitude Resistance Curves

threshold. These results are plotted in Fig. 9 as the closed dots [3 ksi (20.7 MPa)] considering all stress cycles in the spectrum. The damage caused by stresses greater than 4.5 ksi (31.0 MPa) adequately predicted the fatigue failures for all the beams except the failures at a Miner stress range of 3.0 ksi (20.7 MPa) (see open dots plotted below the lower confidence line). This indicates that at details with low stress ranges the damage caused by those stress events less than the constant-amplitude threshold can be significant. Gurney has estimated this effect by considering the effect of increasing crack size and the decrease in number of damaging stress cycles (9). This will place the data points between the extremes shown and does not appear to account for all the damage detected at the lower stress range.

#### COMPARISON BETWEEN LABORATORY AND FIELD STUDIES

Although detailed aspects of fatigue crack growth tend to be complex, particularly during the initial stages of fatigue life, analysis and observations

have provided a considerable understanding of actual behavior. This information should be considered when judgments are made as to the importance of small cracks and local stress elevations due to detail geometry. The long life desired in a bridge structure is unlikely to be obtained unless the time interval necessary for development of visible fatigue cracking is similarly large. Comparison of crack growth behavior in full size (large) cover-plated beams to those in small scale cover-plated beams are of special interest.

**Analytical Crack Growth Behavior.**—Previous studies on welded details (6) indicate that the mean rate of crack growth is related to the stress intensity range by the following equation:

$$\frac{da}{dN} = C \Delta K^3 \quad (3)$$

in which  $C$  = crack growth constant;  $\Delta K$  = stress intensity range; and  $da/dN$  = crack growth rate. The calculation of stress intensity range,  $\Delta K$ , can be formulated in the following manner (1):

$$\Delta K = F(a) \Delta \sigma \sqrt{\pi a} \quad (4)$$

in which  $F(a) = F_E F_S F_W F_G$ ;  $a$  = crack size;  $F_E$  = elliptical crack front correction;  $F_S$  = free surface correction (12);  $F_G$  = stress concentration correction (14);  $F_W$  = finite width correction; and  $\Delta \sigma$  = stress range.

Sharp discontinuities occur frequently along a fillet weld toe due to the inclusion of nonmetallic material (6,8). Inclusions are caused by slag particles which are deposited in the melted base and weld metal. These discontinuities in the high stress concentration zone at the weld toe act as crack initiation sites. The size of a typical discontinuity has been estimated to be approximately 0.015 in. (0.38 mm) long and several thousandths of an inch (hundredths of a millimeter) deep with an extremely sharp root radius of 0.0001 in. (0.0025 mm) or less (8,14).

Multiple cracks usually occur along the toe of any transverse fillet weld. Initially, these cracks which initiate at discontinuities are believed to grow as single cracks. These single cracks tend to grow toward a more circular shape (6) unless they are located in close proximity to each other. As crack growth continues these single cracks begin to coalesce. The formation of merged cracks is random and dependent upon defect size, population, and distribution in the weldment.

Crack size measurements were made on W36  $\times$  230 and W36  $\times$  260 cover-plated beams which had been fractured in the test program reported in Ref. 10. Coalescence results in a decreased crack shape ratio ( $a/b$ ) and a subsequent decrease in fatigue life. Coalescence takes place more rapidly along a straight weld toe than along an irregular weld toe.

Equation 3 with  $C = 2(10^{-10} \text{ in.}^{11/2})/\text{cycle kip}^3$  [ $1.21(10^{-13} \text{ mm}^{11/2})/\text{cycle } N^3$ ] and the lower bound of the crack shape ratio was used to estimate fatigue life for the primary cover plate detail of an interior beam (W36  $\times$  230) at Yellow Mill Pond. Equation 3 is the mean crack growth rate relationship. An initial crack size of 0.04 in. (1.0 mm) and a stress range of 8 ksi (55.2 MPa) was used. The estimated fatigue life was 1,360,000 cycles. This corresponds favorably with the fatigue lives found in Refs. 8 and 10 for similar sized

cover-plated beams. The predicted fatigue life falls below the lower 95% confidence limit for the smaller W14  $\times$  30 end-welded cover-plated beams reported in Ref. 5.

The lower bound estimate for the crack growth rate  $C = 3.6(10^{-10} \text{ in.}^{11/2})/\text{cycle kip}^3$  [ $2.18(10^{-13} \text{ mm}^{11/2})/\text{cycle } N^3$ ] in Eq. 3 was also used to predict the fatigue life for the aforementioned detail. At a stress range of 8 ksi (55.2 MPa) the estimated fatigue life was 750,000 cycles. The lower bound estimate of fatigue life is plotted in Fig. 8 as Category E' and corresponds favorably with the early indications of cracking for the full-scale beams in Refs. 8 and 10 and the lower 95% confidence limit for cover plates wider than the flange.

**Crack Growth Threshold.**—The cover-plated beams which were tested in developing the AASHTO fatigue specification were rolled W14  $\times$  30 (5). The design stress range threshold for Category E was estimated to be 5 ksi (34.9 MPa). The constant-amplitude fatigue tests since conducted at Lehigh University on W14  $\times$  30 end-welded cover-plated beams indicate a stress range threshold of 4.8 ksi (33.1 MPa) as was shown in Fig. 6.

The variable-amplitude fatigue tests indicate that the crack growth threshold stress range under variable loading is below the constant-amplitude threshold. Also, the root-mean-square and Miner equivalent stress range from the variable cycle tests fall within the extension of the 95% confidence limits for end-welded cover-plated beams under constant-amplitude loading (6).

In constant-amplitude tests, Paris has shown that the stress intensity threshold,  $\Delta K_{Th}$ , is mean stress dependent. In addition,  $R$  is defined as the ratio of minimum stress to the maximum stress. As the mean stress or  $R$  ratio increases the stress intensity threshold decreases. At welded details the  $R$  ratio will always be larger due to the tensile residual stress field. This yields a  $\Delta K_{Th}$  near  $3.0 \text{ ksi } \sqrt{\text{in.}}$  ( $3.3 \text{ MPa } \sqrt{\text{m}}$ ).

The stress history studies at Yellow Mill Pond indicate that extensive fatigue cracking would be unlikely to occur if only those stresses greater than  $\Delta\sigma_{Th}$  based on constant-amplitude tests contributed to fatigue damage. This is particularly true for those beams that were subjected to very few stress cycles greater than 3 ksi (20.7 MPa) but have still exhibited detectable cracks.

**Fatigue Life Estimates at Yellow Mill Pond Bridge.**—The root-mean-square and Miner's equivalent stress ranges were estimated based on the 1971 and 1976 strain history studies. These stresses are listed in Table 2. During the 1971 study, truck counts were conducted simultaneously with the strain history. The one-way average daily truck traffic (ADTT) on span 10 has increased from 3,000–6,700 for the years 1958–1975. The percentage of trucks in the total traffic flow has remained roughly constant at 13.5% during these years. This has resulted in approximately 35,000,000 trucks crossing the eastbound and westbound bridges of span 10 during the interval between 1958 and 1976.

The measurements acquired in 1971, 1973, and 1976 were used to construct a composite stress range spectrum for the worst condition. This spectrum provided an effective Miner's stress range of approximately 1.9 ksi (13.1 MPa). If each truck crossing the structure is assumed to result in a single stress cycle, the open point plotted in Fig. 10 would result and falls just below the lower bound fatigue resistance. If more than one stress cycle is assumed to occur as suggested by the few records acquired in 1976, the estimated variable stress spectrum would plot at 62,800,000 cycles using 1.8 events/truck.

The expected residual fatigue life in beams with large cracks is small. Significant fatigue crack growth would be expected to occur between 35,000,000 cycles and 63,000,000 cycles depending on whether or not a single stress cycle or an increased frequency is assumed. The results also suggest that no crack growth threshold exists for this detail when a portion of the stress cycles exceed the estimated constant cycle crack growth threshold.

The original casualty girder failed in 1970 after an accumulated ADTT of approximately 21,000,000 trucks. No stresses were ever recorded on span 11. However, it is readily apparent from Fig. 10 that only small increases in the effective stress range would be necessary for earlier failures.

The fact that at least three-five large cracks, i.e., at least 0.5 in. (13 mm) deep, have been observed in several spans suggests that the results plotted in Fig. 10 are typical for the more highly stressed beams in the bridge structure. Most of the beams with cracks are under the more heavily traveled lanes. Furthermore, the fact that many small cracks have been detected in other beams subjected to lower levels of stress range further confirms the observation that no crack growth threshold apparently exists. Sufficient numbers of higher stress

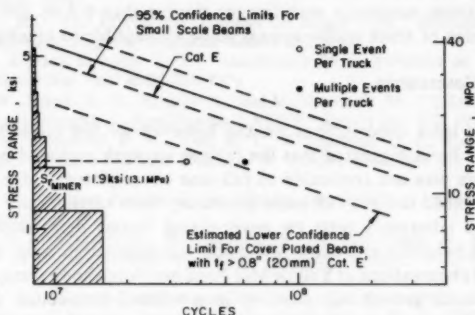


FIG. 10.—Comparison of  $S_{rMINER}$  with Calculated Cycles and Fatigue Resistance of Beam Tests

range events occur, i.e., that exceed the estimated constant cycle threshold of about 2.6 ksi (17.9 MPa), so that all stress range events appear to result in fatigue crack propagation.

It is also apparent from the growth and formation of the fatigue cracks at Yellow Mill Pond, that the fracture toughness of the cover-plated beams was not a significant factor in the development of the fatigue cracks. The 15 ft-lb (20 J) transition temperature for the beam flange was 55° F (13° C). The material toughness satisfied the requirements for temperature zone I. Even though lower service temperatures, i.e., less than 0° F (-18° C), were experienced, this has not had a significant influence on the fatigue resistance of any girder. Stable fatigue crack growth has occurred at every detail with detectable cracks. None of these cracks have shown any evidence of unstable crack growth. These bridge girders emphasize once again the importance of fatigue as a major factor in any fracture control plan.

**Inspection or Retrofitting Other Bridges, or Both.**—The stress recorded at Yellow Mill Pond Bridges are similar to the stresses which have been measured at other cover-plated beam bridges (3) in the United States. Therefore, it is highly probable that the fatigue cracking which has developed at the Yellow Mill Pond Bridges will also be experienced at other comparable cover-plated beam bridges in time as the cumulative stress cycle count becomes comparable.

Very few of the bridge structures shown in Table 3 have exhibited smaller peak stress range conditions. These comparisons suggest that most of these bridges can be expected to exhibit fatigue cracking when subjected to a sufficiently large number of stress cycles. It is also apparent from Table 1 that girders under all traffic lanes have experienced fatigue cracking. The larger cracks as expected are primarily located under the major truck lanes.

The composition of the average daily truck traffic (ADTT) at Yellow Mill Pond is not greatly different than gross vehicle weight distribution from the 1970 Federal Highway Administration (FHWA) nationwide loadometer survey (7). Although other structures may be exposed to different conditions in the composition of the ADTT, utilization of service lanes, and other factors, these are not likely to effect the long term resistance to fatigue cracking. Those cover-plated beam structures with flanges thicker than 0.8 in. (20 mm) subject to large volumes of truck traffic appear to be susceptible to cracking.

#### SUMMARY AND CONCLUSIONS

1. The long term observations on the behavior of the cover-plated beams at Yellow Mill Pond suggested that the fatigue strength provided by small scale laboratory tests was not applicable to full-size cover-plated bridge beams. This reinforced the need to have full-scale laboratory tests carried out.

2. Full-scale laboratory tests on cover-plated beams demonstrated that the observed field behavior at Yellow Mill Pond was compatible with the test data.

3. The field observations at Yellow Mill Pond provided the first major indication that fatigue crack growth can develop in a welded connection when only a few stress cycles in the variable stress spectrum exceed the constant cycle fatigue limit.

4. The observations have also demonstrated that significant cracking can develop when overloads result in stresses exceeding the fatigue limit and large number of stress cycles accumulate (greater than  $10^7$ ).

5. The results suggest that other comparable cover-plated beam bridges [ $t_f > 0.8$  in. (20 mm)] will require retrofitting in the future if subjected to high volume truck traffic.

6. The observations at Yellow Mill Pond have contributed to the adoption of design Category E' for this type of detail.

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The opinions and findings expressed or implied in this paper are those of the writers. They are not necessarily those of the Transportation Research Board, the National Academy of Sciences, the Federal Highway Administration, and the American Association of State Highway and Transportation Officials, nor of the individual states participating in the National Cooperative Highway Research Program.

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# JOURNAL OF THE TECHNICAL COUNCILS OF ASCE

## COMPUTER ANALYSIS AND DESIGN OF STRUCTURES

By Christian Meyer,<sup>1</sup> M. ASCE

(Reviewed by the Technical Council on Computer Practices)

### INTRODUCTION

The extraordinary development of computer-aided structural analysis and design during the last two decades was the result of three separate but interrelated factors: (1) The formulation of matrix theory of structures; (2) the development of finite element theory; and (3) the rapid progress of computer technology.

No single factor alone could have caused the state-of-the-art to advance as fast as it did. The theory of matrices has been a branch of linear algebra for over 100 yr, but it was primarily Argyris' contribution (1) to formulate classical methods of structural theory in matrix notation. This lends itself to elegant programming for digital computers. Nowadays, courses in matrix analysis are regularly incorporated into undergraduate curricula, and numerous texts are available (6,9,12).

Finite element theory dates back to the classical paper by Turner, et al. (14), and is now well-documented in several textbooks (2,4,16). What is so significant about finite element theory is that it allows the extension of classical methods of structural analysis to two- and three-dimensional continua, thus making possible the analysis of arbitrary complex structures such as plates, thin and thick shells, arch dams, and other solids, provided a computer is available to perform the millions of tedious arithmetical operations. It should be noted that finite element solutions are only approximate, although the accuracy is usually adequate for engineering purposes, depending on the fineness of the finite element mesh.

The advances of computer technology can be witnessed almost daily in everyday life as well as in engineering. Speeds of arithmetical operations and sizes of central memory have increased by several orders of magnitude within recent

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years, even though the cost per unit calculation and per unit storage have decreased markedly.

It is the purpose of computer programs or "software engineering" to make the enormous computing power of today's hardware available to the engineer. Such programs can help relieve the design engineer from a considerable burden. The analysis of structures having hundreds or thousands of members or components poses no fundamental problems anymore. The engineer can therefore concentrate his time and attention on those areas that still do pose difficulties, such as a proper mathematical description of the mechanical behavior of engineering materials. But he should also be aware that the sheer power of today's analysis programs constitutes a temptation for substituting automated design or analysis procedures for traditional engineering common sense and judgment.

Computer analysis of structures is an almost perfect tool for today's structural engineer. It is limited only by an engineer's ingenuity and skill, knowledge of the mechanical behavior of materials, and ability to represent the structure by a mathematical model and to correctly interpret the results. A similarly sweeping statement cannot be made yet about structural design software. Although impressive progress has been made in this area, in particular in the field of optimum design, the acceptance of this tool is not nearly as widespread among practicing engineers as is the computer analysis of structures.

It is the primary purpose of this paper to introduce engineers who are not very familiar with computers to the many possible applications in structural engineering. It should be stressed that mastery of finite element technology and sophisticated programming techniques is not a prerequisite for successful usage of the computer. However, it is important that a user be familiar with the basic theory underlying structural analysis and design programs if he is to make efficient use of the computer. This paper addresses mostly potential computer users, as opposed to program developers. It presents some of the theory underlying structural analysis and design programs. The major capabilities of a number of widely-used programs are briefly summarized, and four examples illustrate some typical points of interest.

#### COMPUTER ANALYSIS OF STRUCTURES

In solving structural analysis problems, three sets of conditions have to be satisfied: (1) Equilibrium of all forces applied to any structure joint or node; (2) compatibility of all element displacements at a given node; and (3) constitutive equations representing the force-displacement relationships of all structural elements.

The structural analysis problem is solved in two phases, i.e., there is an element level solution and a structural level solution. In the first phase, elements are considered individually for the derivation of appropriate force-displacement equations. It is this element-level phase in which finite element theory is needed in order to extend the concepts of stiffness or force-displacement relationships, long known for frame members, to elements of two- and three-dimensional continua. In the second analysis phase, the individual elements are assembled to establish equilibrium and continuity of the entire structure.

Most structural analysis programs are based on the direct stiffness solution;

the individual steps of this analysis procedure are briefly summarized in the following.

1. Structure discretization.—For a program user, dividing a structure into discrete elements or members is the most difficult step, compared to which, the subsequent data preparation is relatively straightforward. Particularly, the subdivision of two- and three-dimensional continua into a number of imaginary discrete elements requires considerable skill, experience, and insight into the behavior of structures.

2. Selection of element freedoms.—For each element or element type, degrees-of-freedom have to be selected which adequately represent the element behavior. This choice is usually made by the program developer. The user should only be aware of the selection made. A space frame member, e.g., normally requires six freedoms at each node (three rotations and three translations), while for three-dimensional solid elements, three translational freedoms per node are sufficient.

3. Element stiffness computation.—Once the degrees-of-freedom have been selected, the associated stiffness coefficients have to be computed. For frame members, these coefficients are generally known. The derivation of similar coefficients for elements representing continua such as plates, shells or solids, requires a finite element analysis.

4. Determination of joint loads.—Those loads not directly applied to joints or nodal points, such as gravity loads or pressure, have to be replaced by statically equivalent nodal loads. In frame analysis, these are commonly known as fixed-end forces and moments.

5. Coordinate transformation.—If stiffness coefficients and joint loads common to a particular node are to be added, they have to refer to a common coordinate system. For this reason, element stiffnesses and load vectors are transformed to such a common coordinate system.

6. Assembly of global equilibrium equations.—This is the important step that enforces both equilibrium and compatibility at all structure nodes and is achieved by assembling all element stiffnesses and load vectors into the common structural stiffness matrix and load vector, respectively, to establish one equation of equilibrium for each structure degree-of-freedom.

7. Application of boundary conditions.—In order to prevent large unconstrained displacements, proper boundary conditions have to be applied, such that the structure is externally and internally stable. Numerically, the correctness of applied boundary conditions manifests itself in a nonsingular structure stiffness matrix.

8. Solution of linear equations for unknown joint displacements.—This is generally the most time-consuming step, often taxing even the fastest and biggest computers available today. The large amount of numerical computations and demand on computer memory space can be drastically reduced by taking advantage of the facts that the equations are: (a) Symmetric (because of Maxwell-Betti's law of reciprocity); (b) positive-definite (because the strain energy associated with any mode of deformation must always be positive); and (c) sparse (because of limited connectivity between the various structure nodes, most stiffness coefficients are zero).

9. Computation of element forces and stresses.—Based on the element stiffness

TABLE 1.—Widely-Used General-

Capabilities and options (1)	Program						
	ADINA (2)	ANSYS (3)	ASKA (4)	BERSAFE (5)	EASE (6)	ELAS (7)	FINITE (8)
Element library:							
One-dimensional elements	X	X	X	X	X	X	X
Two-dimensional elements	X	X	X	X	X	X	X
Three-dimensional elements	X	X	X	X	X	X	X
Material options:							
Linear elastic	X	X	X	X	X	X	X
Temperature-dependent	X	X		X	X		X
Elasto-plastic	X	X	X	X			X
Viscoelastic	X	X	X			X	
Loading options:							
Static forces	X	X	X	X	X	X	X
Thermal steady state	X	X	X	X	X	X	X
Thermal transient	X	X					
Harmonic load		X	X				
Transient load	X	X	X				
Inertia load	X	X	X				
Analysis options:							
Static analysis	X	X	X	X	X	X	X
Mode shapes and frequencies	X	X	X		X		
Time history-mode superposition			X		X		
Time history-direct integration	X	X					
Response spectrum		X			X		
Buckling	X	X	X			X	X
Other options/features:							
Large displacements	X	X	X	X			X
Large strains	X						
Substructuring		X	X		X		X
Plotting		X	X	X	X	X	
Interactive		X					X
Interrupt/restart	X	X	X		X		X

formulation of Step 3, it is possible to compute all element forces and internal stresses, once all joint displacements are known.

For further details, see, e.g., Refs. 6 and 12.

If the loading to which a structure is subjected, is of a time-dependent or dynamic nature, such as wind, earthquake, impact, blast, sea waves, or mechanical equipment, each static equation of equilibrium established in the preceding Step 6 will have to be replaced by an appropriate equation of dynamic equilibrium, which takes into account the mass or inertia, as well as damping properties of the structure. These equations can be integrated directly, using established numerical analysis techniques. Often, the structure's natural frequencies and mode shapes of vibration are determined first and used subsequently to transform the dynamic equilibrium equations to modal or normal coordinates. This has the advantage that the subsequent numerical integration can be limited to only the few equations which represent the significant modes of vibration (2).

## Purpose Structural Analysis Programs

Name							
MARC (9)	NASTRAN (10)	NONSAP (11)	SAP4 (12)	SAP6 (13)	STARDYNE (14)	STRU DL (15)	SUPERB (16)
X	X	X	X	X	X	X	X
X	X	X	X	X	X	X	X
X	X		X	X	X	X	X
X	X	X	X	X	X	X	X
X	X	X	X	X			X
X		X					
X							
X	X	X	X	X	X	X	X
X	X	X	X	X	X	X	X
X	X						
X	X				X	X	
X	X	X	X	X	X	X	
X	X	X	X	X	X	X	
X	X	X	X	X	X	X	X
X	X	X	X	X	X	X	X
X	X		X	X	X	X	
X	X		X	X	X	X	
X	X		X	X	X	X	
X	X						
X	X	X				X	
X	X			X	X	X	
X	X			X	X	X	X
X	X					X	X
X	X	X	X	X	X	X	X

Similar numerical integration techniques must be employed if the structure behavior is nonlinear. The nonlinearity may be due either to material nonlinearities, such as plastic yielding, cracking, creep, etc., or geometric nonlinearities, such as large displacements, instability, etc. Instead of analyzing the structure for small time increments as in dynamic analysis, nonlinear problems are analyzed for small load increments.

## STRUCTURAL ANALYSIS AND DESIGN SOFTWARE

In the United States alone there exist literally thousands of structural analysis and design programs. These may be classified as either special-purpose programs or general-purpose programs. Special-purpose programs are limited to a certain application, such as the analysis of continuous beams, planar frames, plane grids, cylindrical shells, etc. General-purpose programs can analyze a variety of different structures, containing libraries of different element types such as

general frame elements, plate bending elements, three-dimensional hexahedrons, etc. Structural design programs are normally to be categorized as special-purpose programs. The complex nature of the structural design process does not yet permit application to general problems. They are restricted to special applications such as reinforced concrete column or frame design, highway bridge girder design, transmission tower design, etc.

Most programs are written by engineers for their own personal use. Graduate students very often in the course of their studies towards higher degrees develop programs characterized by limited applicability, insufficient documentation, and verification and difficult or time-consuming usage. Usually each program has only a single author; he alone knows how to use the program, and after his graduation such a program becomes useless, in most cases. These programs are generally small (up to say 4,000 source statements) and inexpensive to develop (no more than several hundred man-hours). Yet the efficiency in terms of execution speed and storage requirements may be quite advanced, depending on the particular interests of the authors.

General-purpose programs require a team effort because they are large, consisting of usually well over 10,000 source statements and involving at least several man-years of development. Such an investment is justified only if a large number of engineers can be trained in a relatively short time to use the program effectively. The size of such programs is dictated either by the spectrum of analysis capabilities or by the degree of sophistication with regard to user orientation. Adding a new analytical capability to a program may not involve large amounts of additional coding. But if the usage is optimized to require a minimum of user input, the task can become rather complex. For this reason, even special-purpose programs can be voluminous and expensive to develop if they include sophisticated subprograms which make the program usage as easy as possible. Since these features are seldom of academic interest, such efforts are almost always undertaken by industrial users themselves or by commercial software developers specializing in servicing a particular branch

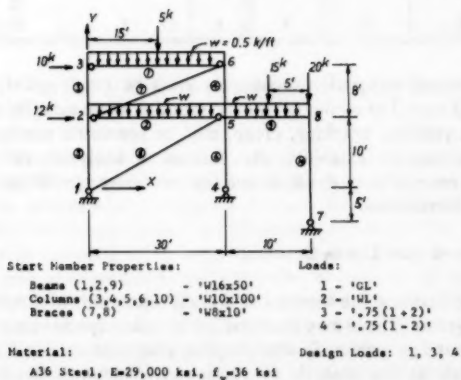


FIG. 1.—Example 1: Plane Frame (1 in. = 25.4 mm; 1 kip = 4.45 kN)

of industry. For example, the investment for the basic capabilities of a piping analysis program may constitute only 20% of the final product, the remaining 80% relate to user-oriented features such as input preprocessors and output post-processors.

Table 1 summarizes some important features and capabilities of a number of widely-used general-purpose structural analysis programs. This list does not claim to be complete, and further information can be found in program surveys such as Refs. 8, 10, and 11. Much of the information of Table 1 was taken from Ref. 11. However, most software developers are constantly improving and extending their programs so that Table 1 is probably not completely up to date. For detailed information, the developers should be contacted directly. Also, the computer networks through which most programs are distributed or accessed are useful sources of information.

Potential computer users should be aware that general-purpose programs are

```

*TITLE '*** GTSTRU DL DEMO-2 ***'
COLBO
STRU DL 'DEMO-2' 'GTSTRU DL DEMONSTRATION'
UNITS KIPS FEET
TYPE PLANE FRAME
JOINT COORDINATES
1 0.0 0.0 S
2 0.0 10.0
3 0.0 18.0
4 30.0 0.0 S
5 30.0 10.0
6 30.0 18.0
7 40.0 -5.0 S
8 40.0 10.0
JOINT RELEASES
1 4 7 MOMENT Z $ PINNED SUPPORTS
MEMBER INCIDENCES
1 3 6
2 2 5
3 2 3
4 5 6
5 1 2
6 4 5
7 2 6
8 1 5
9 5 8
10 7 8
MEMBER RELEASES
1 2 7 8 START MOMENT Z END MOMENT Z
PLOT FORMAT ORIENTATION NON STANDARD
PLOT PLANE
EJECT
UNITS LBS FEET
CONSTANTS DENSITY 490.0 ALL $ PCF
UNITS INCH KIPS
CONSTANTS E 29000.0 ALL
MEMBER PROPERTIES TABLE 'STEELW78'
1 2 9 TABLE 'W16X50'
3 TO 6 10 TABLE 'W10X100'
7 8 TABLE 'W8X10'
UNITS FEET
LOADING 1 'GL'
MEMBER LOADS
1 2 9 FORCE Y UNIFORM W -0.5 $ K/FT
1 FORCE Y CONCENTRATED FRACTIONAL P -5.0 L 0.5
9 FORCE Y CONCENTRATED FRACTIONAL P -15.0 L 0.5
JOINT LOADS
8 FORCE Y -20.0
LOADING 2 'ML'
JOINT LOADS
3 FORCE X 10.0
2 FORCE X 12.0
LOADING COMBINATION 3 '0.75X(1+2)' COMBINE 1 0.75 2 0.75
LOADING COMBINATION 4 '0.75X(1-2)' COMBINE 1 0.75 2 -0.75
QUERY

```

FIG. 2.—Example 1: GTSTRU DL Input





## PORTLAND CEMENT ASSOCIATION

FLAT SLABS & WAFFLE SLABS  
ANALYSIS AND DESIGN

set MANL; type problem description; set AUTO; press "GO".

## FLAT SLAB EXAMPLE FOR THE USER'S MANUAL

## NOTE

- (1) As each data item is requested, it is to be keyed into the calculator, and entered by pressing "GO".
- (2) If requested, key 1 for yes and key 2 for no.
- (3) For columns with capitals, use a fictitious equivalent column -- see the User's Manual for details.

## (1) MASTER DATA

No. of spans = 3  
 Depth of drop in = 4.0  
 Wt. of conc pcf = 150.0  
 Slab T in = 8.0  
 Width of slab ft = 20.0

## (2) SLAB DATA

Span length ft = 21.0  
 L.L psf = 75.0  
 Added D.L psf = .0  
 Partial L.L plf = .0  
 C1 ft = .0  
 C2 ft = .0  
 Count(Ident. sp) = 1

## (2) SLAB DATA

Span length ft = 22.0  
 L.L psf = 75.0  
 Added D.L psf = .0  
 Partial L.L plf = .0  
 C1 ft = .0  
 C2 ft = .0  
 Count(Ident. sp) = 1

## (2) SLAB DATA

Span length ft = 21.0  
 L.L psf = 75.0  
 Added D.L psf = .0  
 Partial L.L plf = .0  
 C1 ft = .0  
 C2 ft = .0  
 Count(Ident. sp) = 1

## (3) COLUMN DATA

Col. T below in = 24.0  
 Col. W below in = 24.0  
 Count(Ident.col) = 4

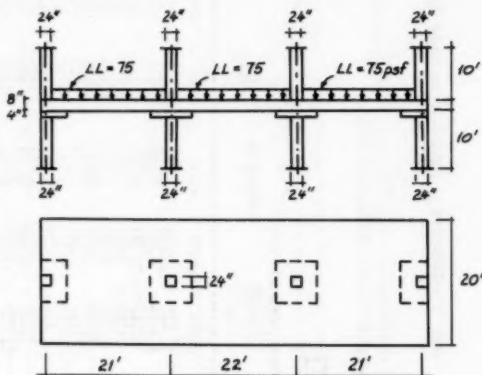


FIG. 4.—Example 2: Flat Slab Design

normally more difficult to use than special-purpose programs, and require more training for effective use. Moreover, if programs with nonlinear analysis capabilities are considered (primarily material nonlinearities), then the degree of difficulty inherent in such problems requires even more sophistication on the part of the user than is necessary for straightforward linear structural analysis problems. On the other hand, special-purpose programs lend themselves to the development

OUT-PUT

(1) PRINT-OUT OF CENTERLINE BEND. MOMENTS AND SHEAR FORCES

Col.no	Pattern 1		Pattern 2		Pattern 3		Pattern 4	
	MOMENTS(ft-kips)							
1	-2.350	-122.720	-1.400	-124.500	-2.350	-56.560	-2.670	-128.300
2	-245.870	-236.870	-209.850	-150.050	-176.090	-206.990	-272.050	-252.980
3	-236.880	-245.850	-150.040	-209.880	-207.000	-176.100	-252.990	-272.070
4	-122.680	-2.350	-124.460	-1.400	-56.530	-2.350	-128.250	-2.670
	SHEAR FORCES(kips)							
1	-4.710	46.700	-2.800	47.040	-4.710	25.430	-5.340	50.950
2	-55.520	55.520	-55.170	32.510	-36.620	53.530	-64.640	60.540
3	-51.570	57.550	-32.500	55.170	-53.540	36.620	-60.550	64.640
4	-44.670	4.710	-47.040	2.800	-25.430	4.710	-50.950	5.340

(2) SHEAR STRESSES

(a) ALLOWABLE SHEAR STRESS (psi) = 252.9

(b) COMPUTED SHEAR STRESSES

COL. NO.	PUNCH STRESS (psi)	WITHOUT TORSION		* SHEAR STRESS (psi)	WITH TRANSFER OF MOMENT				GOVERN. PATTERN
		GOVERN. PATTERN	VERT. REACT. (kip)		GOVERN. PATTERN	VERT. REACT. (kips)	TOTAL MOMENT (ft.k)	BENDING PORT. (ft.k)	
1	63.7	4	54.797	127.4	4	54.797	125.63	75.37	4
2	96.5	4	121.413	102.6	4	121.413	59.80	35.88	2
3	96.5	4	121.421	102.6	4	121.421	59.84	35.90	2
4	63.7	4	54.797	127.3	4	54.797	125.58	75.34	4

(3) DESIGN FOR FLEXURE

(a) NEGATIVE REINFORCEMENT

COL. NO.	DESIGN M. @ FACE (ft-k)	GOVERN. PATTERN	STEEL AREA	
			COL. (sq.in.)	MIDDLE (sq.in.)
1	-80.025	4	1.664	.057
2	-210.085	4	3.343	1.766
3	-210.105	4	3.343	1.766
4	-80.366	1	1.671	.057

(b) POSITIVE REINFORCEMENT

SPAN NO.	MAX. POS. M. (ft-k)	AT POINT (ft)	GOVERN. PATTERN	STEEL AREA (sq.in.)
1	101.716	9.45	4	3.42
2	81.048	11.00	3	2.72
3	101.563	12.07	4	3.42

FIG. 4.—Continued

of specialized problem-oriented input languages designed to permit the user to converse with the computer in a language very similar to his own, in which he is traditionally used to describe his problems. The required learning periods can therefore be very short.

Structural design programs are really special-purpose programs and therefore of such diversity that they do not lend themselves easily to a summary such

as in Table 1. They may be classified though, according to their level of design sophistication.

On the lowest level, programs are written to perform simple stress checks, i.e., stress calculations to check whether the design is in compliance with the applicable code requirements.

Programs of the next higher level are capable of performing simple designs such as selecting rolled steel shapes adequate to carry design forces and moments determined in a previous analysis. Other programs may determine the required steel reinforcing bars and stirrups in reinforced concrete members. The difficulties associated with the design of prestressed concrete structures make automated design programs very effective and time saving, especially if many different construction stages are to be considered, such as in cantilever or segmental bridge construction. Programs of this level of sophistication often have some limited weight or cost optimization capabilities. These are normally restricted to individual member designs, such as beams or columns, or at most, floor designs in steel, concrete, or timber construction. The designer would still have to make most of the fundamental decisions with regard to structural layout, overall member sizes, etc. A limited survey of such design programs can be found in Ref. 10.

#### (4) REINFORCING BAR SCHEDULE

NOTE: Length of bars in ft.

##### (a) TOP REINFORCEMENT (NEGATIVE)

COL. NO.	BAR DIAM.	COLUMN STRIP				MIDDLE STRIP					
		LONG BARS		NO.	SHORT BARS		DIAM.	ALL BARS			
		LEFT LENGTH	RIGHT LENGTH		LEFT LENGTH	RIGHT LENGTH		NO.	LEFT LENGTH	RIGHT LENGTH	
1	# 5	4	1.00	7.27	4	1.00	4.79	# 4	9	1.00	5.17
2	# 5	6	7.90	8.29	5	4.79	4.99	# 4	10	7.90	8.29
3	# 5	6	8.29	7.90	5	4.99	4.79	# 4	10	8.29	7.90
4	# 5	4	7.27	1.00	4	4.79	1.00	# 4	9	5.17	1.00

NOTE: See manual for reinf. concentration due to moment transfer.

##### (b) BOTTOM REINFORCEMENT

SPAN NO.	BAR DIAM.	COLUMN STRIP				MIDDLE STRIP			
		LONG BARS		SHORT BARS		LONG BARS		SHORT BARS	
		NO.	LENGTH	NO.	LENGTH	NO.	LENGTH	NO.	LENGTH
1	# 4	6	20.25	5	17.87	5	20.25	4	17.35
2	# 4	5	21.50	4	16.50	5	21.50	4	15.40
3	# 4	6	20.25	5	17.87	5	20.25	4	17.35

#### (5) MATERIAL QUANTITIES

##### (a) TOTAL SLAB REINF.

Negative steel (lb) = 712.21  
Positive steel (lb) = 738.11

##### (b) OTHER QUANTITIES

Surface area (sq.ft.) = 1320.00  
Yardage of concrete (cu.yd.) = 32.59

(c) Reinf. per sq.ft. in one dir. = 1.098

FIG. 4.—Continued

The highest level design programs are characterized by comprehensive design optimization capabilities. There exist, e.g., a few highway bridge design programs for various bridge types, primarily I-girder bridges. Other programs perform

**SAMPLE PROBLEM 5A ANALYSIS CONDITIONS AND NOTES:**

- 1) Apply ASME Section III - NC3600 (Nuclear Class 2 Code)
- 2) Analyze system subject to "expansion," "sustained," and "occasional" loads

3) Response Spectrum:	FREQ	ACCEL
	.3	19.3
	2.2	135.0
	3.9	135.0
	7.3	1932.0
	14.0	69.6
	32.1	38.6
	60.2	38.6

- 4) Shock 1: 100% in X direction  
67% in Y direction  
Shock 2: 100% in Z direction  
67% in Y direction
- 5) Max mass lump spacing = 3'-0"  
Eliminate mid-points on elbows

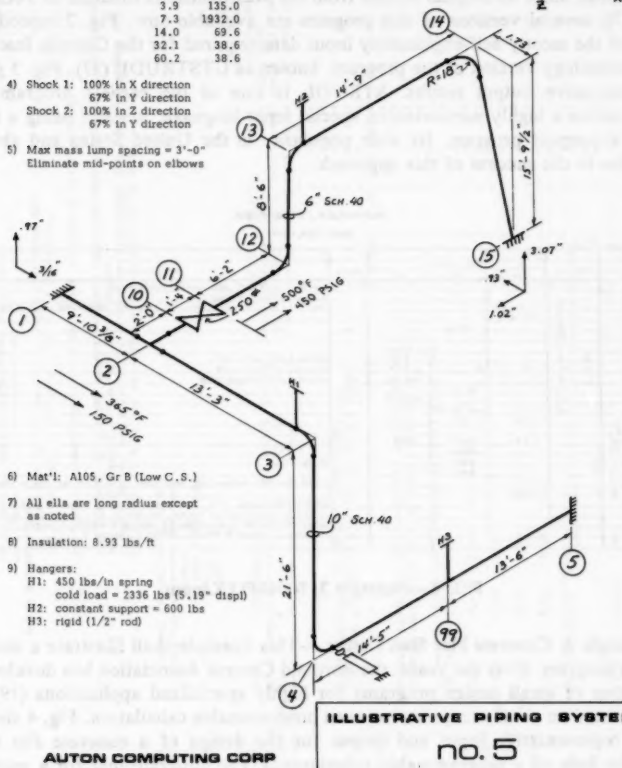


FIG. 5.—Example 3: Piping System (1 in. = 25.4 mm; 1 lb = 4.45 N)

design optimizations for transmission towers or aircraft structure components, etc. (5,13,15).

#### EXAMPLES

Applications of computer programs are as diverse as the field of structural



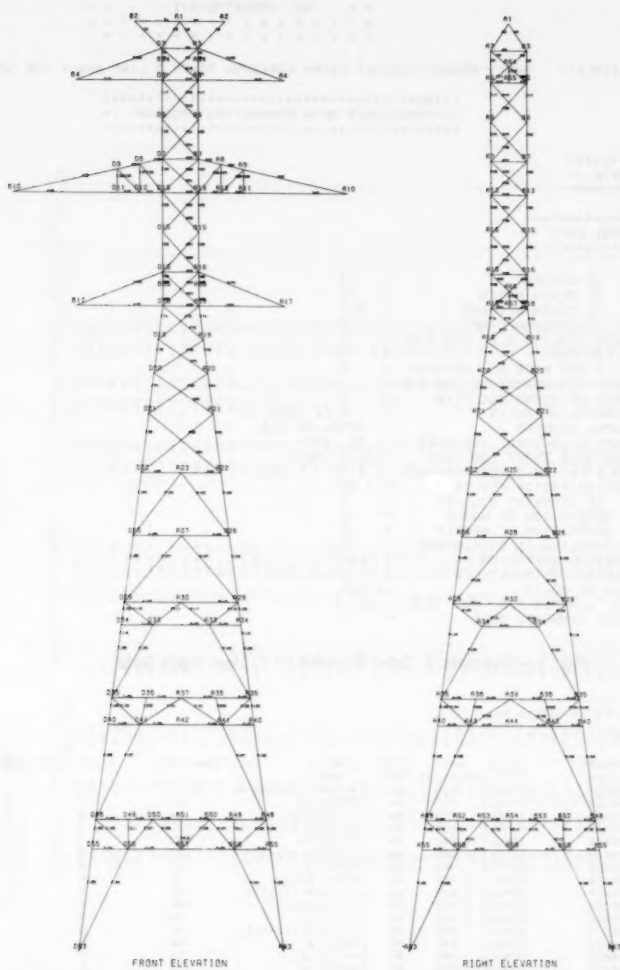


DYNAMICS  
LOADING - WEIGHT & PRESSURE (INCLUDES UNIT)  
INTERNAL FORCES, MOMENTS AND STRESS CALCULATIONS (CONTINUED)

PAGE 43

POINT FILE TYPE	LOC NO.	FORCES (POUNDS)		MOMENTS (FOOT-POUNDS)		SIF		SECTION MODULUS (IN <sup>3</sup> )	LONGITUDINAL STRESS (PSI)
		AXIAL	RESIDUAL SHEAR	TORSION	BENDING	IN-PLANE	OUT-OF-PLANE		
ANCHR	1	7.	716.	367.	1021.	606.	1.00	29.90	1806.
STR -f	1.1	7.	589.	367.	207.	733.	1.00	29.90	1333.
STR -f	1.2	7.	673.	367.	1107.	656.	1.00	29.90	1531.
STR -f	1.3	7.	351.	367.	2120.	583.	1.00	29.90	1886.
STR -f	2	7.	210.	367.	568.	2632.	1.07	29.90	2711.
BR BT	2	6.	123.	66.	517.	2783.	1.07	29.90	2670.
STR -f	2.1	6.	267.	66.	2218.	375.	1.00	29.90	1896.
STR -f	2.2	6.	413.	66.	1208.	233.	1.00	29.90	1488.
STR -f	2.3	6.	561.	66.	246.	91.	1.00	29.90	1102.
STR -f	3	6.	1507.	66.	2146.	51.	2.61	29.90	2677.
MEM -f	3	1083.	1093.	101.	762.	29.	2.61	29.90	1596.
STR -f	3F	1400.	48.	110.	199.	9.	2.61	29.90	1172.
STR -f	3F.1	1355.	48.	110.	183.	119.	1.00	29.90	1091.
STR -f	3F.2	1221.	48.	110.	166.	248.	1.00	29.90	1121.
STR -f	3F.3	1087.	48.	110.	149.	376.	1.00	29.90	1162.
STR -f	3F.4	953.	48.	110.	132.	565.	1.00	29.90	1267.
STR -f	3F.5	819.	48.	110.	115.	633.	1.00	29.90	1255.
STR -f	3F.6	688.	48.	110.	99.	761.	1.00	29.90	1304.
STR -f	4	550.	48.	110.	800.	62.	2.61	29.90	1699.
MEM -f	4	388.	321.	133.	762.	25.	2.61	29.90	1585.
STR -f	4F	47.	453.	78.	339.	117.	2.61	29.90	1280.
STR -f	4F.1	47.	323.	78.	662.	130.	1.00	29.90	1274.

FIG. 7.—Continued



345KV DOUBLE CIRCUIT RIVER CROSSING TOWER O LINE ANGLE FOR SEP

FIG. 8.—Example 4: TRANTOWER Plot of Transmission Tower

```

* * * * *
* * * * *
* * SARGENT & LUNDY ENGINEERS * *
* *   TRAN-TOWER PROGRAM   * *
* *   NO. TRA097101611   * *
* * * * *

```

\*\* JOB TITLE\*\* 345KV DOUBLE CIRCUIT RIVER CROSSING TOWER O LINE ANGLE FOR SEP

```

*****
** TRAN-TOWER MESH GENERATION PROGRAM **
*****

```

```

*****
** INPUT DATA **
*****

```

```

*****
** CONTROL DATA **
*****

```

```

NO. OF GROUPS          = 23
NO. OF GIVEN NODES     = 69
NO. OF GIVEN MEMBERS   = 217
NO. OF LOADING CASES   = 8
INDEX.O=G,1=G & A, 2=G,A & D = 2
NO. OF PLOT            = 1
WRITE OUT NODE NO. ON PLOT = 1
WRITE OUT MEMBER NO. ON PLOT = 1
INDEX OF ISOMETRIC VIEW = 5
DIAMETER OF BOLTS      = 5 /8 INCH
YOUNGS MODULUS         = 29000.00 KSI
SHORT SIDE INPUT FOR PLOT = 25. INCH
LONG SIDE INPUT FOR PLOT = 40.0 INCH
SCALE FACTOR INPUT FOR PLOT = 1 TO 5 .00
REDUCED FACTOR FOR FB  = 1.00
NO. OF GEOMETRY STUDIED = 1
NO GENERATION OF NODES = 0
NO GENERATION OF MEMBER = 0
NO BUCKLING IS CONSIDERED = 0
A DESIGN CRITERION     = .050
ALLOWED DESIGN CYCLES  = 5
TYPE OF BOLTS          = A-394
MAX. L/R FOR TEN. ONLY MEM. = 500.0
TOWER SYMMETRY CODE    = 0

```

FIG. 9.—Example 4: Echo Printout of Typical Input Data

```

*****
** MEMBER SIZES IN GROUPS **
*****

```

GROUP NO.	MEMBER TYPE	ANGLE TYPE (INCH+2)	AREA TYPE	STEEL TYPE	NAME OF ANGLE	LOCATION INDEX	FIXED SIZE INDEX
1	BRACE	SINGLE	.620	36	L1-3/4X1-3/4X3/16	18	0
2	BRACE	SINGLE	.710	36	L2X2X3/16	21	0
3	BRACE	SINGLE	.810	36	L2-1/2X2X3/16	24	0
4	BRACE	SINGLE	.900	36	L2-1/2X2-1/2X3/16	27	0
5	BRACE	SINGLE	1.090	36	L3X3X3/16	33	0
6	BRACE	SINGLE	1.190	36	L2-1/2X2-1/2X1/4	37	0
7	BRACE	SINGLE	1.440	36	L3X3X1/4	41	0
8	BRACE	SINGLE	1.310	36	L3X2-1/2X1/4	38	0
9	BRACE	SINGLE	1.440	36	L3-1/2X2-1/2X1/4	42	0
10	BRACE	SINGLE	1.560	36	L3-1/2X3X1/4	46	0
11	BRACE	SINGLE	1.690	36	L4X3X1/4	49	0
12	BRACE	SINGLE	1.690	36	L3-1/2X3-1/2X1/4	48	0
13	BRACE	SINGLE	1.940	36	L4X4X1/4	58	0
14	BRACE	SINGLE	2.090	36	L4X3X5/16	61	0
15	BRACE	SINGLE	2.400	36	L5X3X5/16	71	0
16	BRACE	SINGLE	1.690	50	L3-1/2X3-1/2X1/4	48	0
17	LEG	SINGLE	2.400	50	L4X4X5/16	72	0
18	BRACE	SINGLE	2.860	50	L4X4X3/8	85	0
19	LEG	SINGLE	4.180	50	L5X5X7/16	109	0
20	LEG	SINGLE	4.360	50	L6X6X3/8	112	0
21	LEG	SINGLE	5.060	50	L6X6X7/16	120	0
22	LEG	SINGLE	5.750	50	L6X6X1/2	125	0
23	BRACE	DOUBLE	3.120	36	L3-1/2X3X1/4	46	0

FIG. 10.—Example 4: Typical TRANTOWER Output

MEMBER NODE NO.		INTERNAL MEMBER NO.		SYMMETRY GROUP MEMBER		LENGTH		UNBRACED LENGTHS		CASE OF	
MEMBER NO.		INTERNAL MEMBER NO.		SYMMETRY GROUP MEMBER		LENGTH		UNBRACED LENGTHS		CASE OF	
1A	1A	2A	513	XZ PL.	1	120.00	120.00	120.00	120.00	1	4
1B	1A	2B	513	XZ PL.	2	120.00	120.00	120.00	120.00	1	4
2A	1A	3A	613	MISC.	12	98.95	98.95	98.95	98.95	1	4
2B	1A	3B	618	MISC.	12	98.95	98.95	98.95	98.95	1	4
2C	1A	3C	629	MISC.	12	98.95	98.95	98.95	98.95	1	4
2D	1A	3D	630	MISC.	12	98.95	98.95	98.95	98.95	1	4
3A	2A	3A	514	MISC.	10	112.57	112.57	112.57	112.57	2	5
3B	2A	3B	515	MISC.	10	112.57	112.57	112.57	112.57	2	5
3C	2B	3C	687	MISC.	10	112.57	112.57	112.57	112.57	2	5
3D	2B	3C	690	MISC.	10	112.57	112.57	112.57	112.57	2	5
4A	3A	3C	619	XZ PL.	4	96.00	96.00	96.00	96.00	2	5
4B	3A	3C	619	XZ PL.	4	96.00	96.00	96.00	96.00	2	5
5A	3A	3B	615	MISC.	12	96.00	96.00	96.00	96.00	2	5
5B	3D	3C	688	MISC.	12	96.00	96.00	96.00	96.00	2	5
6A	3A	3C	616	MISC.	3	135.76	101.82	67.88	67.88	2	5
6B	3B	3D	620	MISC.	3	135.76	101.82	67.88	67.88	2	5
7A	3B	5C	621	MISC.	2	127.56	95.67	63.78	63.78	2	5
7B	3B	5C	621	MISC.	2	127.56	95.67	63.78	63.78	2	5
8A	3A	5A	595	MISC.	12	84.00	84.00	84.00	84.00	1	4
8B	3B	5B	595	MISC.	12	84.00	84.00	84.00	84.00	1	4
8C	3D	5D	576	MISC.	12	84.00	84.00	84.00	84.00	1	4
8D	3D	5D	576	MISC.	12	84.00	84.00	84.00	84.00	1	4
9A	3A	6A	511	MISC.	12	63.78	111.62	63.78	63.78	2	5
9B	3B	6A	512	MISC.	12	63.78	111.62	63.78	63.78	2	5
9C	3C	6A	512	MISC.	12	63.78	111.62	63.78	63.78	2	5
9D	3D	6A	512	MISC.	12	63.78	111.62	63.78	63.78	2	5
10A	5A	3D	596	MISC.	2	127.56	95.67	63.78	63.78	2	5
10B	5A	3D	596	MISC.	2	127.56	95.67	63.78	63.78	2	5
11A	5A	6A	597	MISC.	2	63.78	111.62	63.78	63.78	2	5
11B	5B	6A	597	MISC.	2	63.78	111.62	63.78	63.78	2	5
11C	5D	6A	607	MISC.	2	63.78	111.62	63.78	63.78	2	5
11D	5C	6A	683	MISC.	2	63.78	111.62	63.78	63.78	2	5
12A	5B	5D	628	MISC.	16	96.00	96.00	96.00	96.00	1	4
12B	5B	5D	628	MISC.	16	96.00	96.00	96.00	96.00	1	4
13A	4A	5A	493	MISC.	16	233.00	76.89	76.89	76.89	1	4
13B	4A	5B	495	MISC.	16	233.00	76.89	76.89	76.89	1	4
13C	4B	5D	678	MISC.	16	233.00	76.89	76.89	76.89	1	4
13D	4B	5D	684	MISC.	16	233.00	76.89	76.89	76.89	1	4
14A	5B	6A	608	MISC.	3	67.88	118.79	67.88	67.88	2	5
14B	5B	6A	609	MISC.	3	67.88	118.79	67.88	67.88	2	5
14C	5C	6A	625	MISC.	3	67.88	118.79	67.88	67.88	2	5
14D	5D	6A	626	MISC.	3	67.88	118.79	67.88	67.88	2	5
15A	5A	6A	600	MISC.	6	48.00	96.00	48.00	48.00	2	5
15B	5B	6A	600	MISC.	6	48.00	96.00	48.00	48.00	2	5
15C	5C	6A	674	MISC.	6	48.00	96.00	48.00	48.00	2	5
15D	5D	6A	675	MISC.	6	48.00	96.00	48.00	48.00	2	5
15E	5C	6B	680	MISC.	8	48.00	96.00	48.00	48.00	2	5
16A	5A	6D	601	MISC.	5	142.27	106.70	71.14	71.14	2	5
16B	5B	6C	610	MISC.	5	142.27	106.70	71.14	71.14	2	5
17A	5A	6A	587	MISC.	17	105.00	105.00	105.00	105.00	1	4

FIG. 10.—Continued



program, Fig. 8 shows the overall geometry of a transmission tower, designed by Sargent & Lundy's TRANTOWER program (13). Some selected input and output data are reproduced in Figs. 9 and 10, respectively. This last example was chosen to show that the computer can be used to design structures not only more efficiently, but also better than is possible by only traditional methods.

## CONCLUSION

The four aforementioned examples were selected to convey an idea of the large number of possibilities to which the computer lends itself via large structural analysis and design programs. They illustrate the vast potential of computers to increase the productivity of engineers by freeing them from the tedious and repetitious work associated with hand computations and routine design calculations for more creative and satisfying design work. With computers, more design alternatives can be analyzed and evaluated without added cost in terms of man-hours, compared to which machine costs are relatively small. Better and more reliable designs are the likely result. Complex structures cannot be analyzed and designed anymore competitively without the use of computers.

## ACKNOWLEDGMENT

Acknowledgment is made to the Georgia Institute of Technology, the Portland Cement Association, Auton Computing Corporation, and Sargent & Lundy Engineers, for making available data for the sample problems. The writer is also indebted to the reviewers for their constructive comments.

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# JOURNAL OF THE TECHNICAL COUNCILS OF ASCE

## METRICATION AT WATER AND POWER RESOURCES SERVICE<sup>a</sup>

By E. R. Lewandowski,<sup>1</sup> M. ASCE

(Reviewed by the Technical Council on Computer Practices)

### INTRODUCTION

A message from the White House in April 1979 contained three basic points:

"First, the administration believes that there are significant benefits from metric conversion; second, the administration supports a strong interpretation of the Metric Conversion Act; and third, the administration is taking steps to encourage metric conversion, both in the government and in the private sector."

Expanding on the third point, the message continues:

". . . the administration is working to encourage conversion in a responsible manner in both government and the private sector . . . we are attempting to provide leadership in the metric area; we are attempting to make the government a model of metric conversion."

This paper will consider the experiences of the Water and Power Resources Service in the construction of major projects using SI metric units instead of United States customary (inch-pound) units.

<sup>a</sup>Presented at the April 14-18, 1980, ASCE Convention and Exposition, held at Portland, Oreg. (Preprint 80-086).

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Note.—Discussion open until September 1, 1981. To extend the closing date one month, a written request must be filed with the Manager of Technical and Professional Publications, ASCE. Manuscript was submitted for review for possible publication on April 21, 1980. This paper is part of the Journal of the Technical Councils of ASCE, Proceedings of the American Society of Civil Engineers, ©ASCE, Vol. 107, No. TC1, April, 1981. ISSN 0148-9909/81/0001-0095/\$01.00.

**STATUS OF METRIC CONSTRUCTION IN WATER AND POWER RESOURCES SERVICE**

**Completed Construction Specifications.**—At the present time (winter 1979–1980) two regional specifications have been issued and construction completed using SI metric units. One was for an equipment hatch and hatch cover, and the other was Specifications No. 40-C0641, Channel Cleanup, Flaming Gorge Dam, Flaming Gorge Unit, Colorado River Storage Project. The latter involved removal of 10,000 m<sup>3</sup> of material from the river channel 140 m below the powerplant. The dam and powerplant are located about 68 km north of Vernal, Utah, in Daggett County.

**Present Construction.**—Three major projects are presently being constructed in SI metric units:

1. Choke Canyon Dam, Nueces River Project, Texas (DC-7325).—This \$37,000,000 earthfill structure will be approximately 5,640 m long at the crest with a maximum height of approximately 35 m above the bed of the Frio River. The dam is located about 6.5 km west of Three Rivers in Live Oak County, Texas. It will create an  $881 \times 10^6$  m<sup>3</sup> reservoir. The prime contractor is Holloway Construction and Holloway Sand and Gravel, Wixom, Michigan.

2. Poncha Substation, Fryingpan-Arkansas Project, Colorado (DC-7333).—This \$2,000,000 construction included a service building of 7 m  $\times$  14 m, complete with fixtures, and 230-kV transmission line and substation steel structures. The structure is located approximately 1.6 km southwest of Poncha Springs, Colo. in Chaffee County. The prime contractor is Addison Construction Company of Denver, Colo.

3. Sugar Pine Dam, Auburn-Folsom South Unit, Central Valley Project, California (DC-7360).—This \$20,000,000 earthfill structure will be approximately 181 m long at the crest with maximum height of approximately 55 m above the bed of North Shitrtail Creek. The dam is located near Foresthill in Placer County, California. It will create an 8,500,000-m<sup>3</sup> reservoir. The prime contractor is Auburn Constructors of Danville, Calif.

**Three Major Specifications to be Issued in Late 1979.**—In addition, three major projects are to be constructed in the near future in SI metric units:

1. Hollister Conduit No. 1, San Felipe Division, Central Valley Project, California.—This 1,370 mm diam pipeline will be 2,816 m long. It will be located approximately 2.7 km southwest of Hollister, Calif., in San Benito County.

2. Santo Clara Tunnel, San Felipe Division, Central Valley Project, California.—This concrete-lined tunnel will be about 2,590 mm diam and 1,544 m long. It will be located about 15 km southwest of Gilroy, Calif., in Santa Clara County.

3. Yuma Desalting Plant, Colorado River Basin Salinity Control Project, Title I, Arizona (DC-7401).—This entails site improvement and construction of the pretreatment one facility. Completion of the Desalting Plant will be done under other metric contracts in the near future. The 32-ha site is located approximately 6.5 km west of Yuma, Ariz., and 3 km north of Morelos Dam in Yuma County. Among other things, the initial construction contract involves numerous concrete structures up to 63 m  $\times$  22 m in size.

**Future: Numerous Pumping Plants and Pipelines.**—Future plans are to issue specifications in SI metric units for construction of a number of pumping plants and pipelines, primarily in the Pacific Northwest Region.

#### **BACKGROUND**

The 1975 Metric Policy Act set up a Metric Board whose established policy was to encourage and coordinate Federal efforts in metrication to keep pace with, but not lead, private industry.

The Secretary of the Interior issued Departmental Manual Release No. 2056 in January 1978 containing guidelines for the process of metrication within the Department of the Interior.

There is a firm base in the Federal sector for proceeding with the metrication process. Next we will turn to the private sector. The Associated General Contractors (AGC) was informally polled in 1977 to determine the attitudes of their members towards metric construction. At that time, the majority of the members expressed indifference to whether the specifications were in SI metric or inch-pound units.

The American National Metric Council (ANMC) has recently issued a "Construction Industry's Metric Conversion Schedule."

#### **TRAINING**

Management realized that two major areas had to be covered if metrication were to be successful in the Water and Power Resources Service. First, employees had to be trained; and second, metric standards had to be established in those areas peculiar to the Service's interests. In addition, scheduling for an orderly transition to metric units needed to be accomplished. Consequently, a Metric Committee was formed to accomplish these tasks. To briefly report this Committee's accomplishments, approximately 75% of all Service employees have now had basic orientation in SI metric units, a Metric Manual has been published for the use of the Service employees, and a timetable has been developed for orderly metrication of all elements of Service activities. As an aside, we concluded that a 2-h basic orientation in SI metric units to all employees helped remove many misconceptions, doubts, and fears. However, more detailed training in the use of metric units was withheld until a particular segment of the staff was to be assigned to a project designed using metric units. It took only about an additional 2 h of instruction to prepare our secretaries and technical writers to handle metric units, and also about 2 h additional (in addition to the 2-h basic orientation) for our technical staff to be trained to adequately handle metric units.

#### **EXPERIENCES**

As mentioned previously, the Service has completed a few minor construction jobs using SI metric units and is presently involved in three major construction jobs using metric units. Following are comments from our construction forces and from the contractors and their employees. It must be realized that the

summary of Service experiences encompasses a time frame of only a few years and in no way is to be construed as representative of the construction industry over an extended period of time (see Fig. 1).

**Attitude of Contractors and Contractors' Employees.**—Almost unanimously, the contractors and their employees exhibited an indifferent attitude toward the fact that construction was in metric units. There was no hostility shown; in fact, a number of the employees had previous experience overseas using metric units and consequently were enthusiastic. Some enthusiasm appeared to be generated out of sheer curiosity about the metric system. Most employees adapted readily to the metric units once they began working with them.

**Attitude of Subcontractors and Suppliers.**—Hostile reactions from suppliers were numerous. Many did not want to change methods or shop procedures

	SI DAY										M' DAY									
	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89				
DESIGN SECTOR									8	13							1. Publish metric practice guide for the industry.			
CODES AND STANDARDS SECTORS				1	2				9	10	16				22		2. Develop necessary basic metric standards.			
PRODUCTS MANUFACTURES SECTORS						3	6	7			18						3. Determine product sizes in metric (SI) units.			
CONTRACTORS SECTOR									9	14	17	19	20				4. Decision to build using metric terms.			
LABOR LIAISON COMMITTEE												16					5. Award design contracts for metric buildings.			
REAL ESTATE SECTOR									11						23		6. Develop and distribute product literature.			
USERS SECTOR									4	5	15			21			7. Produce metric measuring equipment.			
SURVEYING AND MAPPING SECTOR				1					12								8. Begin conceptual design in metric terms.			
INFORMATION SECTOR									D	E							9. Publish model codes in metric.			
CONSTRUCTION INDUSTRIES COORDINATING COMMITTEE							A	B	C								10. Develop preliminary estimating systems.			
A. Identify decision-makers and communicate with them regarding opportunities and problems.																	11. Land transactions in metric terms.			
B. Construction industries conference to achieve consensus on conversion schedule.																	12. Produce land and property surveys in metric.			
C. ANMC approved conversion schedule accepted by U.S. metric board. 'SI' DAY set.																	13. Begin design development and engineering.			
D. Publicize official conversion schedule widely.																	14. Produce contract documents in metric.			
																	15. Estimate and bid on metric documents.			
																	16. Award contracts for metric building.			
																	17. Accept plans in metric and issue building permit.			
																	18. Obtain labor agreements in metric.			
																	19. Begin construction of metric building.			
																	20. Deliver metric products to suppliers and site.			
																	21. Install metric products.			
																	22. Complete construction of metric building.			
																	23. Occupy and maintain metric building.			
																	24. Revise metric practice guide.			
																	25. All future real estate transactions in metric.			

FIG. 1.—Construction Industries Metric Conversion Schedule

to turn out metricized materials representing only a small percentage of their work. Many suppliers converted metric dimensions to inch-pound units for their shop use. One supplier could not cut metric threads with his present equipment. Additional costs may be reflected by higher bids from subcontractors and suppliers during a transition period.

**Attitude of Service Employees.**—As with employees of the contractors, the majority of the employees of the Service were indifferent to the fact that they were working with SI metric units. A number of the employees wanted to change to using the metric units as soon as possible. A few of the employees were apprehensive about using metric units, but this apprehension was dissipated once the employees became experienced in the use of metric units. A few employees, the older ones, could not see the reason to change to metric units.

## Effect of Metrication on Costs

1. Contractor.—Two contractors found that aggregate and concrete batch plants were expensive to convert to metric units because of quantity measurement problems. Scale weights for aggregate, cement, and waterflow measurement were difficult portions of the plant equipment to convert to metric units. One contractor estimated it may have cost him \$50,000–\$100,000 to convert his plant to metric units. It also concerned him that he would probably have to convert it back to the inch-pound system after use, since another project using metric units might not be readily available. Rebuilding prebuilt concrete forms such as cable trench forms used on other Service jobs increased the cost to one contractor. Prices from suppliers will probably soon reflect additional costs because suppliers do not want to convert for a small job, e.g., in one instance, resteel suppliers would not furnish metricated steel bars. They dual-dimensioned all steel bars on drawings and furnished them in inch-pound measurements. Most suppliers' shop fabrication was done in inch-pound measure. It has been especially difficult to get price quotations on miscellaneous metalwork specified in metric units.

One contractor's employees in the form yard worked completely in metric with no difficulty. A few estimators have difficulty. A few estimators have difficulty converting production rates and prices from inch-pound frames of reference (rules of thumb) to metric proportions. Some mistakes have occurred on price quotes because of lack of these mental metrical relationships in metric units. One contractor feels he is experiencing more administrative and overhead costs due to problems with metric units. As mentioned previously, these problems have been mainly with suppliers. Prior to bidding, this contractor was minimizing these metric conversion costs, but now he believes they are more significant. His guess would be 5%–10% added cost for metric conversion.

2. Service.—Any increase in costs attributable solely to the use of metric units was in the area of purchase of metric tools and equipment, particularly surveying equipment. One contractor reported that metric survey equipment cost him 5%–30% more than survey equipment using inch-pound units. He also incurred additional costs due to the expense of training employees in metric, converting standard forms to metric, and revising automatic data processing (ADP) programs.

In one instance aerial surveys had to be redone when the project was switched to metric from inch-pound units.

**Effect of Metrication on Scheduling.**—Most contractors reported no scheduling difficulties due to metric construction. However, one contractor did use the wrong metric conversion factor in computations. The contract slipped 1-1/2 months while the error was being corrected. On the other hand, one contractor actually completed his construction ahead of schedule.

One contract was slowed down because of the need to resubmit some drawings for errors in coordinates and dimensions due to incorrect factors used in converting metric and inch-pound system units.

Converting inch-pound ADP programs to metric units sometimes slowed progress. In a few instances, metric-specified items such as rock bolts and metric dial faces were furnished by suppliers in inch-pound units; rectifying

these mistakes caused minor delays. Converting a batch plant to metric units and installing metric reinforcing bars, have also delayed one contract a minor amount.

**Effect of Metrics on Job Complexity.**—Contractors reported that use of solely metric measurements made their jobs considerably simpler primarily due to the elimination of fractions. Employees found the use of decimals instead of fractions much easier and faster. Difficulties arose, however, when inch-pound and metric units were interchanged and mixed. This made the job much more complex. Fortunately, many projects had computer programs to alleviate the problems which arose due to converting metric units to inch-pound units and vice versa. Mixing dimensions on drawings also sometimes resulted in errors and noncompatible measurements. Surveying also is more complex if the surveys are to be done in metric units, but the horizontal and vertical controls are not established in metric units. Employees charged with monitoring water quality have noted that the use of metric units has made their jobs much simpler.

A few contractors mentioned that a delay in converting to metric will continue to cause problems due to the need to use both metric and inch-pound units.

**Effect of Metrication on Safety.**—Both contractors and Government forces were unanimous in stating that the use of metric units had absolutely no impact on the safety aspects of their jobs.

**Availability of Metric Tools and Equipment.**—Most contractors and Service forces experienced difficulties in obtaining metric surveying equipment such as "ad-on" survey tapes and metric drafting scales. One office had difficulty in obtaining metric cross-section paper.

#### SUMMARY AND RECOMMENDATIONS

**Training.**—A brief orientation in metric units about 2 h in length would aid greatly in allaying the fears of employees facing working with metric units for the first time. Most employees, both contractor and government, find working with metric units easier than working with inch-pound units, providing the entire project is using metric units of measurement exclusively.

**Avoid Dual Units.**—Almost unanimously, the opinion was that most difficulties to date with construction in metric units have been due to the fact that both inch-pound and metric units were used in the same contract. Most offices found the use of metric measurements only made the jobs more simple than when inch-pound units only were used, as the inch-pound system is basically more confusing. Consequently, it is recommended that both metric and inch-pound units of measurements should not be used interchangeably within the same contract.

**Allow Additional Costs of 5%-10% Because of Metrication during Transition Period.**—It has been stated that most construction suppliers do not like metric units. Converting inch-pound equipment and supplies into metric equipment and supplies could increase construction costs by as much as 5%-10%. This 5%-10% increase in costs will probably be reflected in the future when bids are submitted for construction jobs designed in metric units.

This situation will correct itself very rapidly on jobs large enough for the bidding to be thrown open to Japanese or European suppliers.

# JOURNAL OF THE TECHNICAL COUNCILS OF ASCE

## GOLDEN GATE BRIDGE: DECK INVESTIGATION<sup>a</sup>

By Harry D. Reilich<sup>1</sup> and Frank L. Stahl,<sup>2</sup> F. ASCE

(Reviewed by the Technical Council on Research)

### INTRODUCTION

When plans were made to bridge the Golden Gate many, including so-called experts, claimed that it could not be done. They pointed to the great depth of water, the turbulent and fast-moving tide, and the fierce winds moving through the straits as obstacles which man was not equipped to overcome. As it stands today, the bridge bears witness to the genius of its designers, and the tenacity of the men who built it.

However, nature had one weapon left in its arsenal: the salt-laden air and fog which persists in haunting the structure. When the bridge operators decided on an extensive repainting program in the middle 1960s, it quickly became apparent that the bridge structure had suffered severe corrosion damage. Consequently, the Golden Gate Bridge, Highway and Transportation District engaged Ammann & Whitney to undertake a complete inspection of all structural components of the suspension bridge and its approaches. This work was performed in 1968 and 1969.

This inspection resulted in the complete replacement of all suspender ropes and their connections to the stiffening truss, completed in 1976, and various repairs to the steel work which, depending on criticality, were handled as emergency or routine maintenance work.

During this inspection it was also observed that the roadway slab was extensively cracked and that it had separated from the supporting stringers in many locations.

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Since the condition did not appear to be of a critical nature, it was recommended that a more detailed inspection of the roadway slab and its supporting elements be undertaken, and methods be developed to arrest the apparent deterioration. This investigation was carried out by Ammann & Whitney between 1971 and 1976. Because of the critical nature of the inspection results, the district arranged for an independent investigation by the California Department of Transportation (Caltrans). A joint report by the two inspecting teams in 1978 recommended early replacement of the present roadway slab.

#### DESCRIPTION OF ROADWAY SLAB AND SUPPORTING FLOOR SYSTEM

The Golden Gate Bridge extends 9,152 ft (2,790 m) between end abutments. It consists of three distinct parts: the suspension bridge proper, the San Francisco approach viaduct, and the Marin approach viaduct.

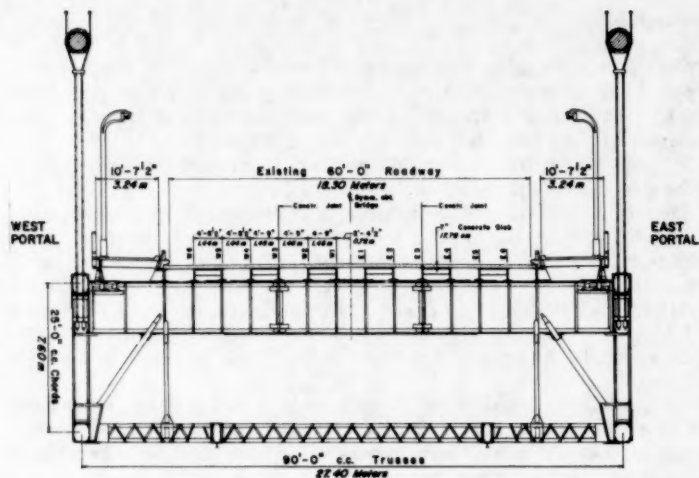


FIG. 1.—Typical Cross Section

The roadway on the suspended structure is 60 ft 0 in. (18.3 m) wide (see Fig. 1). The slab is of reinforced concrete construction, 7 in. (0.18 m) thick. The specified ultimate compressive strength of the concrete after 28 days was 4,000 psi (27.6 MPa). The main steel reinforcement, placed transverse to the center line of the bridge at 6-in. (0.15-m) spacing, consists of reinforcing bar trusses made of smooth 11/16-in. (17.5-mm) diam top and bottom bars arc-welded to a 7/16-in. (11.1-mm) diam smooth web bar bent into a Warren truss pattern. The longitudinal reinforcement consists of 1/2-in. (12.7-mm) diam deformed bars at the top, and 3/4-in. (19.1-mm) diam deformed bars in the bottom layer. All reinforcing steel is of structural grade with a specified minimum yield strength of 33,000 psi (227.5 MPa), and a minimum ultimate strength of 55,000 psi (379.2

MPa). The plan dimensions for top and bottom concrete cover over the reinforcing steel are 1-3/8 in. (34.9 mm) and 1 in. (25.4 mm), respectively.

The transverse reinforcing bar trusses are supported by small steel blocks which are tack-welded to the top flanges of the longitudinal stringers. The bottom surface of the concrete slab is in a plane with the top of the stringer top flange; small triangular concrete haunches protect the edges of the stringer flange (see Fig. 2).

Transverse expansion joints are located at 50-ft (15.25-m) intervals and are 3/4-in. (19.1-mm) wide. These joints coincide with the location of the suspender ropes. Two longitudinal construction joints divide the roadway slab into three approx 20-ft (6.1-m) wide sections. The reinforcing bar trusses are discontinued at these two longitudinal joints.

The floor system supporting the concrete roadway slab consists of 24-in. (0.61-m) deep longitudinal stringers resting on the top flange of 8-ft 6-in. (2.6-m)

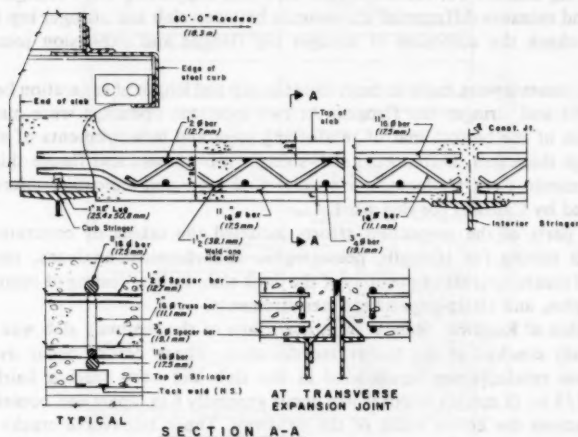


FIG. 2.—Roadway Slab Details

deep transverse floorbeams. The rolled-section stringers are spaced approximately 4 ft 9 in. (1.45 m) on centers; they are continuous over two floorbeam panels ending at the transverse expansion joints. The lower flange of the stringer is fastened to the floorbeams at the center and one end while the other end is free to expand.

Construction of the roadway slab and supporting floor system on the approaches is similar to that of the suspended structure. In the curved roadway sections, the spacing of stringers varies and towards both abutments the normally 60-ft (18.3-m) wide roadway widens out.

#### DECK INVESTIGATION

**Field Inspection.**—The roadway top surface was repeatedly inspected for the

full length from both sidewalks to check for cracks, spalls, delaminations, joint conditions, and the general condition of the riding surface. In addition, large areas of the roadway were inspected closeup during closures of the east and west curb lanes. Chain-dragging operations were performed over large areas of the bridge to search for delaminations in the concrete.

Reinforcing steel was exposed by removing concrete along transverse cracks to determine the condition of the top mat of reinforcing steel, crack sizes, and crack penetration. Holes were cut about 4 in. (0.10 m) wide, 16 in. (0.41 m) long, and 3 in. (0.075 m) deep, exposing the top bar of the transverse reinforcing truss and longitudinal distribution steel.

Inspection of the underside of the roadway slab was carried out from the interior maintenance scaffolds and had to be interfaced with the painting and maintenance operations. The objective of this inspection was to: (1) Determine locations and sizes of cracks and spalls in the concrete deck soffit; (2) check the bearing contact between concrete slab and supporting steel stringers, and locate and measure differential movements between slab and stringer top flange; and (3) check the corrosion of stringer top flanges and expansion joint edge beams.

Measurements were made to determine the gap and length of separation between slab soffit and stringer top flanges. At two locations openings were made for inspection of the bottom mat of reinforcing steel and measurements of stringer top flange thickness. Differential slab-stringer movements and flange thickness measurements were made with a special C-shaped dial-indicating micrometer developed by Caltrans for this work.

Other parts of the inspection efforts included the taking of concrete cores and their testing for strength, petrographic and chemical analyses, electrical potential measurements of portions of the deck slab, fatigue testing of reinforcing bar samples, and strain-gage stress measurements.

**Condition of Roadway Slab.**—The top surface of the roadway slab was found extensively cracked in the transverse direction. These cracks occur over the steel truss reinforcement embedded in the slab and vary from a hairline to approx 1/8 in. (3 mm) in width. They occur generally 6 in. apart and occasionally extend across the entire width of the roadway. These transverse cracks occur with almost uniform frequency throughout the length of the main bridge and both approaches; many of these cracks extend through the full depth of slab.

In addition to the transverse cracking, smaller cracks perpendicular to the main cracks and running along the longitudinal reinforcing steel occur over the entire width of roadway, with larger longitudinal cracks appearing over supporting stringers. A third configuration of cracks, arranged in an irregular crazed pattern, exists primarily in the outside lanes (see Fig. 3). In addition to the considerable cracking, large areas of the roadway have been damaged by scaling and spalling. At several locations where the top mat of reinforcing steel was exposed, either for inspection or during repair of spalled areas, the reinforcing steel was found to be in good condition except for an occasional light layer of tight rust.

At the 3/4-in. (19.1-mm) wide transverse expansion joints, water leaking through the joint seal has caused corrosion of the top flanges of expansion joint edge beams and top flanges of stringers in this area. The force of the expanding corrosion products has caused offsets between adjacent sides of the

expansion joint and the continuous pounding of wheels has resulted in the breakage of concrete edges throughout the entire bridge. The installation of neoprene preformed compression seals in 1970 has stopped the entrance of water and temporarily arrested the ongoing corrosion. However, the bond between the seal and concrete face is beginning to break down, permitting water to reenter, and corrosion to continue.

The slab is separated from the supporting top flange of stringers at many locations. Two very distinct types of separation were encountered (see Fig. 4). Near the roadway expansion joints, at the end support of the two-span continuous stringer, corrosion of the stringer top flange caused by water seepage

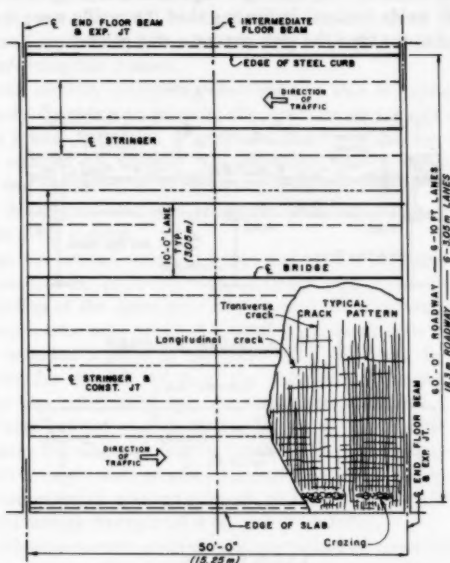


FIG. 3.—Typical Crack Pattern

through the expansion joint has forced a separation of the concrete slab from the stringer top flange. This separation is generally in the nature of a hairline separation, more pronounced along the edges of the flange, and it appears that the slab is still adequately bearing on the stringer at these locations.

The other separation of the roadway slab from the supporting stringer, considerably more pronounced, exists over the intermediate floorbeam (in the middle section of the two-span continuous stringer), and extends for some distance either side of the intermediate floorbeam. This separation measured from 1/16 in.-1/2 in. (1.6 mm-12.7 mm) maximum. The separation between roadway slab and stringer was checked by insertion of a 1/16 in.  $\times$  12 in. (1.6 mm  $\times$  300 mm) long feeler gage which generally could be inserted across the full width

of flange and pushed along the stringer for a considerable distance. In some instances, the gap between the slab and stringer was fully packed with rust. Surprisingly, many other separations between slab and stringer top flange were completely clear, with no indications of rust remnants.

At two locations, the slab soffits were cut open for inspection and flange thickness measurements. In one location, the original red lead paint system of the stringer was intact, with full slab bearing in this area. The rebar truss-supporting block was resting on the top of the stringer with no broken welds visible. At the other location, the stringer had large pits with signs of corrosion on both the top and bottom of the top flange. The truss-supporting block was not in contact with the top flange and had a layer of cement grout under it with all welds broken, indicating that the welds were broken and the block was raised at the time the slab concrete was placed.

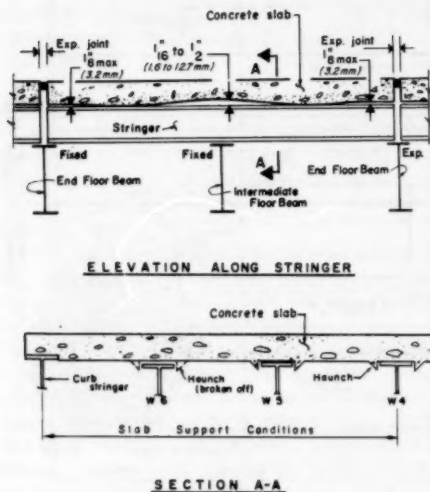


FIG. 4.—Slab Separation

The performance of slab and stringer in areas of separation was carefully observed during the passage of traffic loads in several locations. It appears that the individual behavior of the slab and the supporting stringer is quite normal and in accordance with design theories, each deflecting under the passage of the heavy load immediately above. The space between the bottom of slab and top of stringer reduced somewhat under the passage of load, but the larger gaps generally did not close up. This observation was verified by corrugated cardboard shims which were left in place for 24 h, or for two rush-hour periods. The undamaged condition of these shims verified that, at this location, the slab had not deflected sufficiently to come into bearing at any time during this period. While it therefore appears that in some areas the roadway slab

is not supported in the conventional manner on one or several adjacent stringers, deflection measurements confirmed the absence of high stresses. No distress indications were found which could be directly attributed to this support condition.

Spalling of the concrete haunches along the edges of stringer top flanges was observed throughout the length of the bridge. This spalling is an ongoing condition, as was evidenced by fresh spalls on recently-painted stringers. As a rough guess, approx 30% of all haunches have spalled off completely, with many more weakened to the point of almost immediate failure. This condition by itself has little effect on the safety of the slab but could become a safety hazard for water-borne traffic.

Several areas of spalled concrete on the underside of roadway slab, exposing reinforcing bars, were located. In other areas, indications of the formation of new spalls were found. This defect is obviously caused by rusting of the bottom bar of the reinforcing bar trusses.

The steelwork directly supporting the roadway slab is exposed to corrosive attacks primarily from fog enveloping the structure and water seeping through the expansion joints. Corrosion is restricted mainly to the top surface and the edges of the stringer top flanges. The resultant loss of metal, as far as can be measured and observed, is minimal and does not exceed 1/16 in. (1.6 mm) of the metal thickness. This loss presently does not affect the safe carrying capacity of the floor system.

**Core Testing.**—A limited concrete coring and testing program was undertaken involving cores of 6-in. (0.15-m), 4-in. (0.10-m), and 2-1/4-in. (0.06-m) diam. Visual examination of the cores generally showed the concrete to be in excellent condition. Many cores were taken at a crack location directly over a supporting stringer, and included a piece of the reinforcing bar truss. In some cases the cracks extended for the full depth of the slab; in other cases cracks stopped at or near the top reinforcing bar. At some core locations a space between the bottom of slab and top of stringer was found, confirming the slab separation; in other locations the slab was resting tightly on the supporting stringer.

Compressive strength tests on cores secured from three widely-separated areas of the bridge indicated an average strength of 5,285 psi (36.4 MPa), considerably in excess of the design strength of 4,000 psi (27.6 MPa).

A detailed chloride content analysis was performed on cores taken from various locations on the bridge. The results (see Fig. 5) show that the average chloride content of the concrete adjacent to the reinforcing steel near the riding surface of the deck is about 0.8 lb/cu yd (0.47 kg/m<sup>3</sup>), which is approaching the threshold level of about 1.0 lb/cu yd (0.59 kg/m<sup>3</sup>). No significant corrosion of the top mat of reinforcement causing concrete spalling is anticipated until the chloride contamination increases. However, a statistical analysis of the data indicates that about 9% of a large sample of cores would contain more than 1.0 lb of chloride per cubic yard (0.59 kg/m<sup>3</sup>) of concrete, which appears to be consistent with the limited amount of spalling experienced to date. Therefore, although deck delamination may not be significant at this time, it will progress with time.

The average chloride content of the concrete adjacent to the bottom layer of reinforcing steel is about 1.7 lb/cu yd (1.00 kg/m<sup>3</sup>). This is above the threshold level for corrosion to occur. A statistical analysis of the data indicates that on a large sample about 83% of the cores would exceed 1.0 lb/cu yd

( $0.59 \text{ kg/m}^3$ ), and about 31% would exceed  $2.0 \text{ lb/cu yd}$  ( $1.18 \text{ kg/m}^3$ ) of concrete. This chloride analysis indicates that it is too late to be concerned with preventing a corrosive level of chloride from accumulating in the concrete adjacent to the soffit mat of reinforcing steel. While corrosion-caused spalling

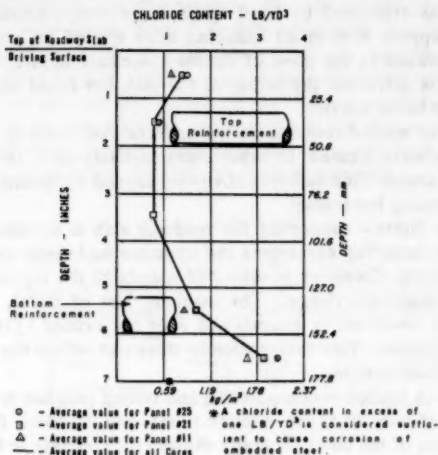


FIG. 5.—Chloride Content of Deck Cores

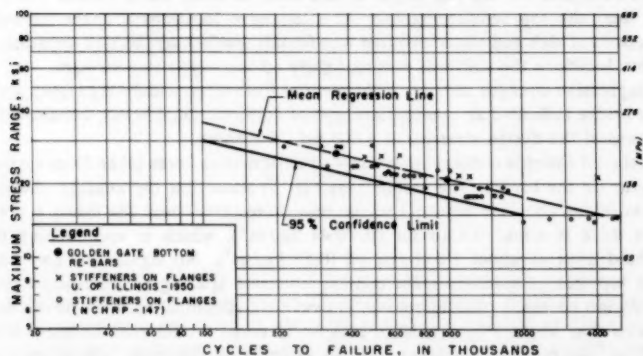


FIG. 6.—Fatigue Behavior of Reinforcing Bars

currently occurs only in a minor area compared to the total surface area of the roadway slab, the corrosion of the soffit steel is expected to continue and evidence of concrete distress on the lower surface of the roadway slab is expected to accelerate.

Reinforcing bar samples removed from concrete test cores were tested for strength and possible fatigue damage. The tensile test indicated a yield strength of 37,855 psi (261.0 MPa), an ultimate tensile strength of 61,050 psi (420.9 MPa), and elongation in 2 in. (51 mm) of 33.7%. All these values exceed the minimum requirements for structural grade billet steel reinforcing bars specified in the original construction.

Considerable concern was felt about the fatigue resistance of the reinforcing steel. For most bridge decks, the reinforcing steel is not welded, and fatigue is rarely a problem. However, the reinforcing bar trusses in the Golden Gate Bridge roadway slab are fabricated by welding, which lowers the life expectancy

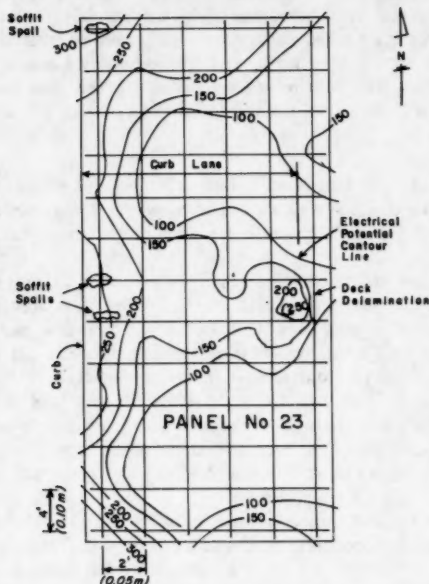


FIG. 7.—Electrical Potential Measurements

of the reinforcement. Fatigue tests were plotted together with published research data of similar test series and show close correlation with these previous tests (see Fig. 6). It was concluded that the tested bars have suffered little or insignificant fatigue damage as a result of the loadings to which they have been subjected during their service life in the bridge roadway, and that the reinforcing bar trusses could safely perform their function under present traffic load conditions and without fatigue failures for considerable additional time at the actual existing stress range established by field measurements.

**Field Measurements.**—Electrical potential measurements together with corresponding visual observations were made on several panels of the roadway slab

(see Fig. 7). Plots of these measurements exhibit the presence or absence of corrosion-caused concrete distress. The delaminations and soffit spalls found by visual inspection can be related to the greater numerical values of the measured half cell potentials, CSE (Saturated Copper-Copper Sulfate half cell). Corrosion is usually associated with readings of  $-300$  mV or more. This is evidence that corrosion of the reinforcing steel is electrochemical and indicates that the cause is related to chloride contamination of the concrete. Readings lower than  $-250$  mV indicate that no corrosion is occurring in this area.

Considerable concern about the stress level in the reinforcing bar trusses was created by the discovery of gaps between the slab soffit and stringer top flange at many locations. Calculations indicated that the apparent absence of normal support could create conditions which eventually would lead to fatigue failure of the slab. In a limited stress measurement program, strain-gage readings were taken both for moving traffic and for stationary loads at predetermined positions. A comparison of stresses calculated for the positions of stationary load application with measured stresses indicated a comfortable margin of safety.

#### LIFE EXPECTANCY

Considerable thought was given to the effect of the various defects on the life expectancy of the roadway slab. The most damaging fact appeared to be the discovery of the high chloride ion content in the area of the bottom reinforcement.

A statistical analysis of the test results shows that at present 83% of the concrete adjacent to the bottom mat of reinforcing steel contains at least 1.0 lb of chloride ion per cubic yard ( $0.59 \text{ kg/m}^3$ ) of concrete and that for about one third of the slab area the chloride content exceeds 2.0 lb/cu yd ( $1.18 \text{ kg/m}^3$ ). Eight yr-10 yr from now it must be expected that the entire slab area will contain at least 1.0 lb/cu yd ( $0.59 \text{ kg/m}^3$ ), and 40% of the area will have a chloride ion content exceeding 2.0 lb/cu yd ( $1.18 \text{ kg/m}^3$ ). At that time, not only will the entire bottom mat of reinforcing steel be exposed to corrosive attacks, but for more than one third of it corrosion will have progressed at a considerable rate for a long time.

Rust has been found to exert a force of 4,700 psi (32.4 MPa), many times the tensile strength of concrete. Laboratory testing has shown that less than 1 mil (0.03 mm) of corrosion loss of a reinforcing bar was sufficient to crack 7/8-in. (22.2-mm) thick concrete, about the thickness of concrete cover under the bottom mat of the roadway slab. Eight yr-10 yr from now rust sufficient to cause cracking and spalling of the slab soffit may be present over more than one third of the slab area. Aside from the very real danger for water traffic from falling chunks of concrete, such loss of concrete cover under the reinforcing steel will greatly reduce the structural safety of the slab. The reinforcing steel will lose bond with the surrounding concrete, causing increased deflection and cracking of the concrete and eventual failure of the slab.

The condition of the riding surface, and the increased frequency of repair of scaled and spalled areas, in particular along the edges of expansion joints, also caused considerable concern. A sharp rise in the incidence of defects requiring repair must be anticipated in the near future. It was concluded that the slab in its current condition and without any but emergency repairs would begin to suffer uneconomic maintenance cost within the next 8 yr-10 yr.

**REHABILITATION STUDIES**

Considering the great difficulty and high cost of replacing the roadway slab, extensive studies were made to develop methods for the repair of the various types of defect. It was concluded that a general rehabilitation of the slab was technically feasible and could extend the useful life of the present roadway some 12 yr–15 yr. After that time, further rehabilitation measures, or replacement again would have to be considered.

Cost studies indicated that complete roadway slab replacement at this time would provide the most dependable solution at the lowest total life cycle cost, and replacement was recommended.

**DECK REPLACEMENT PROGRAM**

**Criteria.**—Except for ferry boats, the bridge provides the only convenient connection between San Francisco and the northern counties where a large percentage of San Francisco's work force lives. With an annual traffic count of 36,000,000 vehicles, one of the prime considerations in the planning for the deck replacement is the requirement that operations should not interfere with the use of the bridge by motorists, especially the daily commuters.

Traffic studies and vehicle counts were carried out to determine how many roadway lanes must be available in either direction at each hour of the day to accommodate normal traffic demand. Obviously, all six lanes are necessary to carry the daily morning and evening rush-hour load. In the late morning and early afternoon and throughout the night, however, a number of lanes can safely be taken out of operation and made available for replacement work. The closure of three lanes nightly from Monday–Friday will permit replacement operations to be performed in a safe and economical manner. During late morning and early afternoon hours on weekdays, the closing of one or two traffic lanes will permit performance of secondary operations on deck level, whereas other preparatory or clean-up operations can be performed below deck at any time without affecting bridge traffic.

**Concept Studies.**—Considering lane configuration and longitudinal joint location of the present and future slab, and given the lane closure parameters developed through traffic studies, various replacement sequences were investigated. The options included replacement of the 60-ft (18.3-m) wide roadway in six, five, or four sections, all 50 ft (15.25 m) long—the length of the present slab between transverse joints. Investigations indicated that the handling of roadway sections approx 15 ft (4.6 m) wide and 50 ft (15.25 m) long is within the capability of available equipment. At the same time, this size results in the least number of replacement units and, consequently, the shortest construction period. Four-section replacement, therefore, becomes the preferred solution.

A large number of slab construction types were investigated for possible application. Included therein were several types used recently on other bridge deck replacement projects, as well as most other types normally used in bridge deck construction, such as precast stone concrete and lightweight concrete, precast prestressed concrete, concrete-filled steel grid floors, and orthotropic steel construction. Schemes included the placing of the new slab on existing stringers; and the removal of the existing stringers with the old roadway slab

and reuse of these stringers or new stringers integrally cast with the new slab at the same or a revised stringer spacing.

From this multitude of possible construction methods, three solutions were eventually selected for final concept study, based on their obvious advantages in constructability, weight, cost, performance, and life expectancy over the other schemes. These three concepts were precast lightweight concrete, concrete-filled steel grating, and orthotropic steel construction.

Because roadway replacement must be accomplished in a piecemeal fashion, the repetitiveness of the suspension bridge and portions of the approach structures lends itself to the concept of modular construction. However, in order to provide a smooth riding and long-lasting bridge deck, the new slab must be made continuous in the transverse direction for the entire width of the roadway by fully effective splices between the individual placement sections.

Previous investigations had indicated the generally acceptable condition of the present stringers. Studies have indicated operational and economic advantages for removing the stringers with the old slab and re-erecting them cast integrally with the new slab. For the major portion of the work, stringers are interchangeable and additional stringers would have to be purchased only to get initial replacement operations started. The old stringers from the initial operation will be available to replace any stringers found defective because of excessive corrosion.

Different stringer spacings were investigated for the new slab. However, there are definite advantages for retaining the present stringer spacing in view of the fact that: (1) The vertical alinement can easily be duplicated by reusing the present shims at each individual location; and (2) there is no need to drill new holes in the floorbeam flanges for stringer seats and to install new bearing stiffeners on the floorbeam webs.

Inspection of other installations has led to the conclusion that, even under the most favorable conditions and with best workmanship, any new riding surface installed in the piecemeal fashion dictated by traffic conditions on the bridge would be of a quality unacceptable to Bay Area motorists. Therefore, the new roadway will, after completion of the entire installation, receive a final epoxy-asphalt overlay to assure smooth riding quality.

#### CONCEPT ALTERNATES

**Precast Concrete Construction.**—The proposed precast concrete scheme (see Fig. 8) is constructed of lightweight aggregate concrete, 7 in. (0.18 m) thick to provide the stiffness required for long life performance. All reinforcing steel bars are epoxy-coated in accordance with Federal standards to provide protection against chloride ion attack. Concrete additives can be employed to minimize the chloride ion problem.

The old roadway slab will be removed with the stringers and these stringers will be recycled and cast integrally with the new slab. The new slab will be designed for composite action, using shear stud connectors. Stringer spacing will remain the same as in the present construction.

Transverse continuity of adjacent slab sections can be obtained by mechanical joints using high-strength bolts or by splice-welding of reinforcing steel and small closure pours. Connection of the new slab to the floorbeams will be by bolts, using the same holes—except for the new fascia stringer necessary

to provide for a widened curb lane—as in the present construction. After completion of the entire installation, the new deck will receive an overlay paving of epoxy-asphalt.

**Concrete-Filled Steel Grating Construction.**—The proposed concrete-filled steel grating (see Fig. 9) consists of transverse I-beams, 4-1/4 in. (0.11 m) high,

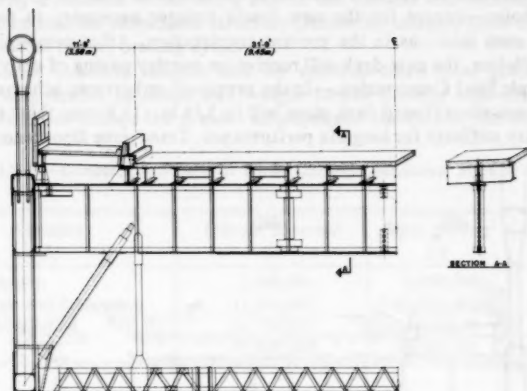


FIG. 8.—Precast Concrete Slab Scheme

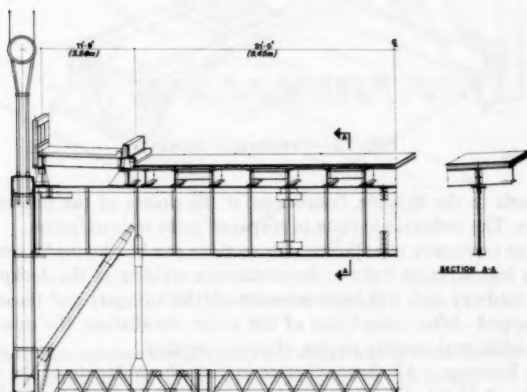


FIG. 9.—Concrete-Filled Steel Grating Scheme

and two layers of longitudinal reinforcing steel bars welded to the I-beams. The grating will be filled and overlaid to a total depth of 6 in. (0.15 m) with lightweight aggregate concrete.

The old roadway slab will be removed with the stringers and these stringers

will be recycled and reinstalled integrally with the new slab. The grating will be attached to the stringers with strength welds to provide composite action. Stringer spacing will remain the same as in the present construction.

Transverse continuity of adjacent slab sections can be obtained by mechanical joints using high-strength bolts or by splice-welding of I-beams and small closure pours. Connection of the new slab to the floorbeams will be by bolts, using the same holes—except for the new fascia stringer necessary to provide for a widened curb lane—as in the present construction. After completion of the entire installation, the new deck will receive an overlay paving of epoxy-asphalt.

**Orthotropic Steel Construction.**—In the proposed orthotropic scheme (see Fig. 10), the closed-rib stiffened deck plate will be 5/8 in. (15.9 mm) thick to provide the necessary stiffness for long life performance. Transverse floorbeams transfer

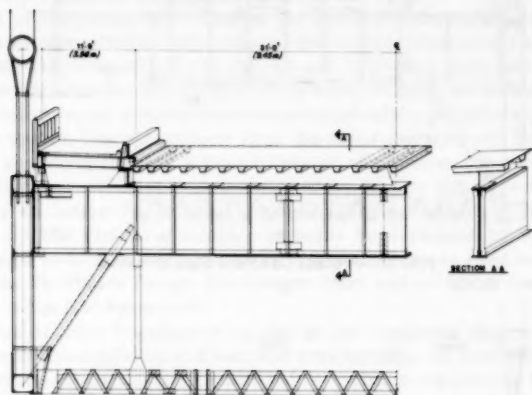


FIG. 10.—Orthotropic Scheme

the slab loads to the existing floorbeams at the points of the present stringer connections. The orthotropic plate is prepaved prior to installation.

Transverse continuity of adjacent slab sections can be obtained by mechanical joints using high-strength bolts or by continuous welding of the deckplate.

The old roadway slab will be removed with the stringers and these stringers will be scrapped. After completion of the entire installation, the new deck will receive an additional overlay paving of epoxy-asphalt.

**Common Features.**—All three schemes include the widening of the curb lanes to 11 ft 0 in. (3.35 m), for a total roadway width of 62 ft (18.9 m); the moving of the sidewalk to provide for the additional roadway width; and the strengthening of the present traffic curb.

**Weights.**—The following shows the unit weights of the three concept schemes. The weight includes the 62-ft wide roadway slab, final overlay paving, stringers, diaphragms, and connections to floorbeam. The weight of the present slab is indicated for comparison: (1) Present slab—114 lb/sq ft (557 kg/m<sup>2</sup>); (2) precast concrete scheme—103 lb/sq ft (503 kg/m<sup>2</sup>); (3) concrete-filled steel grating

scheme—96 lb/sq ft (469 kg/m<sup>2</sup>); and (4) orthotropic scheme—69 lb/sq ft (337 kg/m<sup>2</sup>).

**Costs.**—The construction cost of the three concept schemes, based on January 1980 prices, is estimated in Table 1.

**Aerodynamic Considerations.**—The aerodynamic characteristics of the bridge are primarily a function of its shape and of the vertical and torsional stiffness of the cables and the suspended structure (stiffening trusses, floor trusses, and top and bottom lateral bracing systems).

The precast concrete scheme and the concrete-filled steel grating scheme are both comparable in shape and weight to the present roadway slab, and will therefore not change the present aerodynamic stability of the bridge.

TABLE 1.—Construction Cost of Three Concept Schemes, in 1980 dollars

Variable (1)	Precast concrete (2)	Steel grating (3)	Orthotropic (4)
Mobilization	2,850,000	2,850,000	2,230,000
Materials and fabrication	11,500,000	17,000,000	16,000,000
Field installation	14,750,000	14,750,000	12,670,000
Total	29,100,000	34,600,000	30,900,000

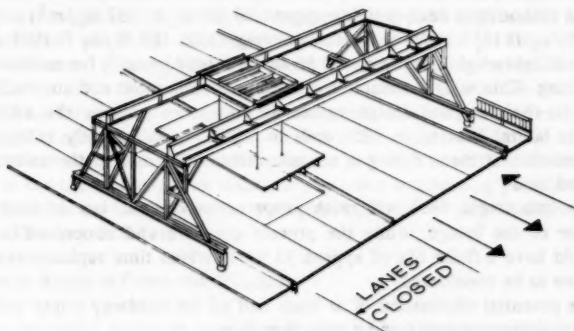


FIG. 11.—Erection Gantry

The orthotropic scheme would result in a considerable reduction in slab weight. However, the effect on the aerodynamic behavior of the bridge will be insignificant.

The outboard movement of the sidewalk will have no effect on aerodynamic characteristics.

**Construction Procedure.**—Methods of fabrication and erection will, in accordance with normal practice, be left to the ingenuity and resources of the construction contractor. Studies were made, however, to prove the feasibility and constructability of the proposed deck replacement program.

Fabrication of the deck units can be accomplished in existing shops in the

Bay Area or in a yard especially established by the contractor in an industrial area along the Bay. Shipment to the site will be possible by barge to an existing dock in Fort Baker. From there, the deck units can be transferred to the west parking area at the Marin end of the bridge which would serve as the contractor's staging area.

The primary erection equipment could be a gantry crane system riding on both sidewalks and spanning clear across the roadway (see Fig. 11). This equipment would be used to remove the old roadway section, transfer it to a waiting flatbed truck, pick up the new section from its truck, and place it into the roadway. This gantry can remain on the bridge throughout the contract period since it does not interfere with traffic.

Proper organization will be the key to a successful operation by the contractor. Time-motion studies indicate that several deck sections can be replaced nightly and that it should be possible to complete the entire field operation within 21 months.

#### FINAL SELECTION

Of the three design concepts, the orthotropic steel deck was selected over precast lightweight concrete or concrete-filled steel grating for the following reasons:

1. The orthotropic deck weights approx 69 lb/sq ft ( $337 \text{ kg/m}^2$ ) compared to 114 lb/sq ft ( $557 \text{ kg/m}^2$ ) for the existing deck, 103 lb/sq ft ( $503 \text{ kg/m}^2$ ) for precast lightweight concrete, and 96 lb/sq ft ( $469 \text{ kg/m}^2$ ) for concrete-filled steel grating. This weight reduction will return main cable and suspender rope stresses to their original design values as they were prior to the addition of the lower lateral bracing in 1956 and, in addition, will greatly reduce tower and foundation stresses during a seismic disturbance due to the reduction of deck dead load.
2. The orthotropic deck will, with proper maintenance, last as long as the remainder of the bridge, while the precast concrete and concrete-filled steel grid would have a finite life of approx 50 yr, at which time replacement would again have to be considered.
3. The potential elimination of at least half of the roadway joints will result in lower maintenance costs and a smoother ride.
4. The orthotropic deck will result in a lower paint maintenance cost due to a reduction of steel edges exposed to weathering and the elimination of the present stringers.
5. Maintenance cost of the lightweight concrete slab is considerably higher due to the need for several surface sealing operations during the life of the slab.

While the initial cost of the orthotropic steel deck scheme is estimated to be approx 6% greater than the lowest cost scheme—precast lightweight concrete—comparative life-cycle cost estimates project a saving for the orthotropic scheme of approx \$4,675,000 over a 50-yr period in maintenance, plus the cost of replacing the deck again in 50 yr.

# JOURNAL OF THE TECHNICAL COUNCILS OF ASCE

## METHODS OF ACCESS TO COMPUTING FACILITIES

By John M. McCormick,<sup>1</sup> M. ASCE

(Reviewed by the Technical Council on Computer Practices)

### INTRODUCTION

This paper will be a chapter in the proposed ASCE *Introductory Manual of Computer Services*, which is being prepared by the Committee on Coordination within ASCE. It is not fully self-contained, because it will follow a chapter on the role of computers in civil engineering practice and will precede chapters on hardware, software, acquiring a computer, and typical applications areas.

This chapter will try to explain and give advice on the problem of getting started in the use of computing machinery to solve engineering problems. The potential user may choose service bureaus, consultants, in-house facilities, or any combination of these methods. The strengths and weaknesses of each method are examined after the stages in the solution of a typical problem are explained. Finally, some suggestions and techniques are provided to aid the user in getting started in the use of computing machinery to solve engineering problems. These are presented in the form of a set of guidelines that warn of pitfalls and encourage the users to "get their feet wet."

### METHODS OF ACCESS TO COMPUTING FACILITIES

There are many facets to the solution of a typical problem using computing systems. We will define each area briefly and then explore the roles that consultants, service bureaus, and in-house facilities may play in rendering assistance in each area. In general, it is probably best to gain experience using these three resources in the preceding order given, but many firms combine all three approaches on any one job.

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## SOLUTION STAGES

A typical solution to an engineering problem, using automated data processing equipment, involves modeling the physical problem, preparing input and other preprocessing activities, solving the model on some computing system, and interpreting the output, plotting results, preparing reports, and other forms of post-processing. We shall consider each of these stages briefly in what follows.

**Preparing Models.**—The first step in solving a problem is to select a suitable model of the physical problem. This is also the most critical step and the choice of a model is seldom trivial, because it is often influenced by previous experience and considerations of the later steps. If the problem is a common one, there may be many computer programs available which could solve it; the choice among these nearly equal alternatives may be based on such secondary considerations as ease of preparation of the input data (e.g., a special purpose program to generate this data may have been prepared while solving a previous problem), or the availability of a particular plotting feature or a restart capability, or a certification by some government agency. The most common mistake in solving problems by computer is freezing the development of the models too early. It is important to take the time at this stage to consider alternative models carefully.

A good beginning to the modeling process is to identify a sequence of models, ranging from coarse approximations (which give the gross outlines of the solution) up to models with many fine details. Such a sequence of models should be designed so that each one builds on the previous models, thus allowing the results from successive models to be somewhat comparable, and reducing the work of constructing each model since some elements of the preceding one can be utilized. It is not intended that all of these models will necessarily be implemented but the process of considering them helps in visualizing the complete problem. This is the time to have your best people think about the problem. It is a particularly good time to call in a good consultant who can guide you in the development of your models based on all the aforementioned considerations, and many others. It is not unusual for a consultant to argue convincingly that one of the simpler models will give the best solution to your problem, better than the solution from your most detailed model. In fact, unneeded details in the model are often counterproductive. A good consultant will often examine your most complete model and chop off spurious details until the reduced model contains just the degree of complexity you need to obtain the information content you require. The savings in this procedure are often dramatic. In recent times, there was a well-known consultant from Columbia University who was noted for occasionally convincing his clients that a simple hand calculation would yield the required answer (after he had been called in expressly to perform large-scale computations on structural systems). It is very common for unexperienced engineers to propose models which are more elaborate than their problem requires.

After a set of models has been carefully chosen (subject to possible modification as they are processed), the problem of data preparation can be addressed.

**Data Entry and Preprocessing.**—Once a given model has been selected for processing, the task of preparing data must be considered. Among the things to be specified are the details of the geometry, the identification of the elements,

the loadings, the relevant physical and material properties, and the form of the output. This task may range anywhere from the simple (involving only a few items if previous data can be modified or data generation routines can be utilized), through the extremely onerous (if vast amounts of data have to be prepared, and if there is much manual data entry to be performed).

There are many useful suggestions that an experienced person or a good consultant can provide to ease the problems of data entry. Sometimes, if the model is appropriately constructed, the solution program can generate much of the repetitive data or supply acceptable default values. It is often desirable to create special coding to prepare input files which can later be processed. Input can be determined directly from plots and drawings using digitizers. It is often unnecessary to be buried under a massive data-entry job if the advice of someone competent can be obtained.

It is most important to be able to preprocess the input data before the major calculation is begun. Various graphics devices are very valuable for this stage. Sometimes they are driven by the solution program, but more often they are independent packages which allow users to display all the details of their models or any subassemblies of them. The data should be stored in such a way that it can easily be updated or modified (e.g., by using editing capabilities) as the model is reviewed. It is also a good idea to save a copy of the model in some permanent form so it can easily be regenerated many years from now if there is a sudden desperate demand to exercise that model again—a surprisingly common occurrence.

Once the data is prepared and verified, the processing of that model can begin.

**Computer Solution.**—The next stage is the actual solution of the problem using some program operating on some central processing unit.

The choice of the program was presumably made at the modeling stage because the details of the model are often tailored to the specific strengths of some code. If a code is known to have certain superior elements, an effort is often made to include them in the model just as the inferior aspects are avoided. Codes are often chosen on the basis of previous favorable experience, ease of preparing input, convenient forms of output, and for other similar considerations independent of the principal solution capabilities of the code. Again, the advice of experienced colleagues and consultants is valuable.

Once the solution code has been chosen, it is often possible to run it on many different central processors. There are many trade-offs to be considered among units with different operating characteristics, memory sizes, and peripheral devices. It is often economical to process on an expensive unit with a memory large enough that out-of-core memory can be sparingly used. And many vendors have such complicated pricing schedules, with many options on priority and class of services, that an expert's opinion is almost mandatory to choose among dozens of possible vendors scattered all over the country, but all commonly available through telecommunications at little or no cost to the user.

The results of the execution are often stored on one or more permanent files so they can be selectively processed at later times. These permanent files may be located on magnetic disks, tapes, cartridges, cassettes, or other auxiliary devices.

**Post-Processing.**—Even after the solution has been obtained, much work

remains to be done. The output from the run must be processed and interpreted. If the model had many elements it is often best to leave the bulk of the output on an off-line file, and process it selectively. Various graphics systems are a huge help in interpreting output through curves and cross plots of related results. It is often desirable to plot some of the results from the latest execution against previous results, or other solutions, or experimental results, all stored in files on off-line devices. It is not unusual to create specific-purpose software at this juncture to sort the results and order them in various ways. Modern graphics and editing systems can display and cross plot results from many sources and present them in report quality form. These considerations are often paramount in the previous choice of models and solution codes.

Engineers must decide how to apportion the tasks in each of these four stages among consultants, service bureaus, and their in-house facilities.

#### TYPES OF ACCESS

There are many ways for engineers to have access to computing facilities for the solution of a problem. They can make use of consultants, service bureaus, and in-house facilities to do all or part of the aforementioned solution stages. The role of the consultants is perhaps the easiest to evaluate.

**Consultants.**—The engineer can call on the services of one or many consultants to do all or any part of the various stages described earlier. This is often sensible when the project or approach being considered is novel.

In particular, it is possible to engage a consultant to obtain the entire solution for you, i.e., to prepare the model, handle the data entry, obtain the computer solution, and do the post-processing. This choice is often made when the engineer is attacking a particular problem by computer for the first time. It is useful to see how one skillful organization handles all the steps in the process. But usually, as engineers develop their own techniques, they prefer to retain control of the solution process and hire consultants as needed who are experts in one or more of the basic solution steps. The same consultant will often give advice on the modeling and solution stages, since they are so closely related. But different consultants may well be used for the data-entry and post-processing phases.

The more often you solve a particular problem, the less likely you are to require a particular consultant's services at each stage, but there is one other role of the consultant which should not be overlooked—i.e., participating in meetings with clients. Often the most valuable service that consultants render is participation in review meetings. They can defend the details of the model to the client, and explain the advantages of the codes you have chosen to solve the problem. The responsibility for the solution is yours, but the consultant can often demonstrate that it is the best solution that could be obtained under the circumstances.

**Service Bureaus.**—Either in conjunction with a consultant or not, you can use service bureaus for any of the problem stages we have examined. Most service bureaus have technical representatives who act in many respects like consultants. They will advise you on details of the models, help with the data entry, and suggest various modes of post-processing. Their knowledge of their

codes and their operating systems makes them very helpful. And, in many cases, the account representative is even more helpful since they are often former technical representatives who can help you in every aspect of the endeavor. It is doubtless true for the inexperienced computer user that the personnel of the vendor are often more critical in the choice of vendors than are the hardware and software systems they represent.

The more highly skilled you are, the less help you need from the vendor's people, and you can choose among the vendors on the basis of available codes and hardware characteristics. But, even in that case, there is considerable interaction with the vendor. There are inevitably difficulties that arise (the system goes down; files are lost; your job is too large or runs too long to be processed without special consideration) that are solved more easily if you have a good relationship with the vendor.

**In-House Facilities.**—As you become more experienced as a computer user, it is economical to depend less and less on consultants and service bureaus as you do more of the work yourself. Recent years have seen a cycle in which, at first, computer users gradually gave up on their own central processors and began to rely on remote computing on super-processors located at central sites. The users only in-house equipment was input/output terminals. This is the "utility" concept of data processing. It implies that it is economical for there to be relatively few, but very large, sources of computer power from which many users can efficiently be supplied through teleprocessing. But as the cost of central processing units has continued to decline, a point has been reached where it is now economical for users to again possess their own processors. This concept is called "distributed processing" and the availability of very low-cost, but amazingly powerful, mini- and microprocessors makes it very attractive, especially since such units are usually modular in their architecture so that new modules can be added as they are required, without making obsolete or replacing the existing components.

Such small processors can do an enormous number of tasks:

1. They can serve as powerful, intelligent terminals in which many of the details (baud rate, sign-on procedures, etc.) are preprogrammed, and available as execution time options.
2. They can be used with digitizers to convert data from graphs or drawings.
3. They can be programmed to generate data.
4. They can be used as central processors to solve all but the largest problems.
5. They can be used as graphics display devices to exhibit the input in many modes, e.g., perspective, general oblique, and section views of the entire model or any subassembly.
6. They can be used to cross plot results (from many diverse calculations against each other and against externally generated data, such as results from experiments). It is a pleasure to sit before a graphics microprocessor and, in a few minutes, display many variations of cross plots, changing the scales, and the component curves at will, until you find the best form to present the desired results. You make a hard copy only of the pleasing combination. All the other variations existed only momentarily on the screen, then vanished forever. You thus consider many alternatives but waste little paper and time since you make copies of only the most successful of your efforts.

7. They can drive various forms of hard-copy devices including electostatic printers and pen-and-ink plotters.

Such small processors can often be upgraded so they can grow with your workload by the addition of modules: high-speed printers, card readers, tape drives, disks, more memory, etc. Many offices eventually combine several small processors in such a way as to complement, or interact with each other, or both.

### GETTING STARTED

The key to getting started is to begin somewhere. Learn by mistakes, if you must. There are so many computing systems, so many possible options, that there is no sure, safe path. Trade journals frequently carry articles about careful professional managers who, in retrospect, bought the wrong equipment. But the choice must be made. One workable philosophy is to buy high-quality equipment and let your best people exercise it. The collection of maxims given in the following can perhaps give some concrete suggestions.

**Some Suggestions and Techniques.**—It's very difficult to give general advice on getting started in computing because the right move depends on many factors, such as the personnel available, the firm's financial position, etc. But there are some general rules that we can give:

1. Get the brightest people available. Computers are only as good as the people who use them.
2. Appreciate the value of a "critical mass"—see the following section.
3. Try promising new products—see the section on "Service Bureaus."
4. Remember that computing is a service industry—see the last section.
5. Let a project get you started. It is often possible to use a large project as the means to expand your computing horizons. If such a project can carry a significant portion of your computing costs for a year or so, then the capabilities so generated will often generate enough work to sustain further growth.
6. Cut your losses when you can. If a piece of equipment fails to become cost effective after a thorough test, don't be afraid to get rid of it and take your loss. This frees some funds for endeavors which may be more successful. Even the best people in this field make frequent errors. Cut your losses.
7. Allow room for growth. Try to structure your facilities so that they can be expanded so your computing power can grow as it's needed.
8. Be alert. The computing industry changes so rapidly that you have to be constantly vigilant. There are many trade papers (e.g., *Computerworld*) and magazines (e.g., *Datamation*, *Byte*, *On Computing*), and it is a good idea to look at them occasionally, as well as at the technical journals in your field, so that you have a feel for the current state-of-the-art.

Some of these rules are amplified in the sections that follow.

**Concept of Critical Mass.**—In order to use computing equipment effectively, you generally need a "critical mass" of people. This means that if you have only one good person to work with your computing equipment, he will generally be inefficient. He will waste too much time being puzzled by simple troubles

which may be easily rectified by a second person. But even two or three good people may not have seen most problems or be expert in enough areas. But with five or six or more good people interacting well together, the chances are high that one of them will have a useful suggestion for any problem that might come up. We shall term such a supportive group of people a "critical mass."

If you have such a "critical mass," it pays to be somewhat adventuresome. This means that you should buy equipment for its own merits and not try to anticipate exactly who will use it or for what project. Consider the following example. A major manufacturer announces a new product, a computer graphics terminal which is a self-contained microprocessor with many options. Your firm has been doing more and more graphics and this processor seems desirable because of its capabilities to both plot as a terminal for remote processing and to produce plots "in-house" from locally-generated data. But the processor can only be programmed in the BASIC language and, despite all their expertise in FORTRAN, PASCAL, and assembly languages, no one in your critical mass knows BASIC. There is a chance that if you acquire this hardware, it will just sit around and be neglected. But our experience has been that, if the equipment has great potential, someone in the "critical mass" will quickly master BASIC and the others will presently combine to use the equipment very effectively.

So, once you have such a "critical mass," which incidentally may include your consultants and the representatives of your vendors, it pays to acquire equipment which gives you new computing powers and simply trust that your group will somehow utilize it effectively.

But, sometimes, a piece of equipment will be underutilized. In those cases, cut your losses, and get rid of the offending hardware. In this connection, it is useful to remember that computing equipment may be rented or leased rather than purchased and these options enable the user to gain flexibility and not get locked into specific hardware. But it should be noted that the question of obsolescence is often exaggerated. Many people are still happily using computing equipment which has not been marketed for many years now. If it works well, why get rid of it?

**Remember Computing is Service Industry.**—Even if you are technically highly competent, the quality of the vendors' service can make a great deal of difference in your computing efforts. This service can take many forms, from the marketing area through technical advice.

There are many ways in which knowledgeable marketing representatives can save you time and money. Examples include the following:

1. They can suggest ways to upgrade your system that seem unlikely. One of the problems that occurs frequently is the purchase or long-term leasing of a piece of equipment subsequently made obsolete by the introduction by the same vendor of a more desirable model. Don't despair too quickly. Ask the marketing representative if there is any way you can cancel your lease on the old model and obtain the newer version. Sometimes, surprisingly, you find you can do just that.
2. They can sometimes suggest purchase options.
3. They can help you choose among many billing options.
4. They can serve as part of your "critical mass."

Further details on hardware, software, and acquiring computing systems will be given in subsequent chapters of the proposed manual.

# JOURNAL OF THE TECHNICAL COUNCILS OF ASCE

## ACQUIRING A COMPUTER

By Elias C. Tonia, <sup>1</sup> M. ASCE

(Reviewed by the Technical Council on Computer Practices)

### INTRODUCTION

The objective of this paper is to provide a civil engineer with a useful guide to acquiring a computing system. Although primarily intended for the neophyte user, it could prove valuable to the veteran consumer who faces a wider market than he did years ago.

Shopping for a computer is indeed time consuming, expensive, and hard work. The major obstacles facing a prospective computer consumer is overcoming a fear which is attributed to: (1) Unfamiliarity with the task; (2) inability to identify current and future computer needs; (3) inability to project the future of the business and the affordability of the computer; (4) availability of a market with a wide variety of hardware; and (5) an industry changing so rapidly that it is difficult to keep up with the latest developments.

To overcome this fear, the civil engineer, being a professional in the planning design, construction, or operation of engineering projects or facilities, or both, for which he specifies the use or incorporation of various equipment, may use a similar approach in the design of his own computer center. First the engineer surveys his needs and identifies the general concept of the project. Then he identifies the various vendors that could provide him with the necessary equipment and service. Next he prepares the necessary contract documents (plans and specifications). Finally the project is advertised, bids are opened, reviewed, and a contract is awarded.

This paper postulates that the key to the successful procurement of a computer incorporates: (1) A sound engineering approach to vendor research, the preparation and evaluation of an objective request for proposals, and the preparation for the computer arrival; and (2) a sound business approach to the negotiation

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and financing of the computer. If handled properly the process of acquiring a computer could become an educational and rewarding experience.

The following describes, step-by-step, important points to consider when purchasing a computer. Figure 1 depicts in bar-chart form the various steps and their duration. For presentation purposes the figure shows the time chart for converting a fairly good size existing installation. The time period will vary depending upon software, hardware, and user sophistication.

#### INITIAL JUSTIFICATION

New developments in computer hardware make the establishment of an in-house computer center feasible for many civil engineering firms. The availability of

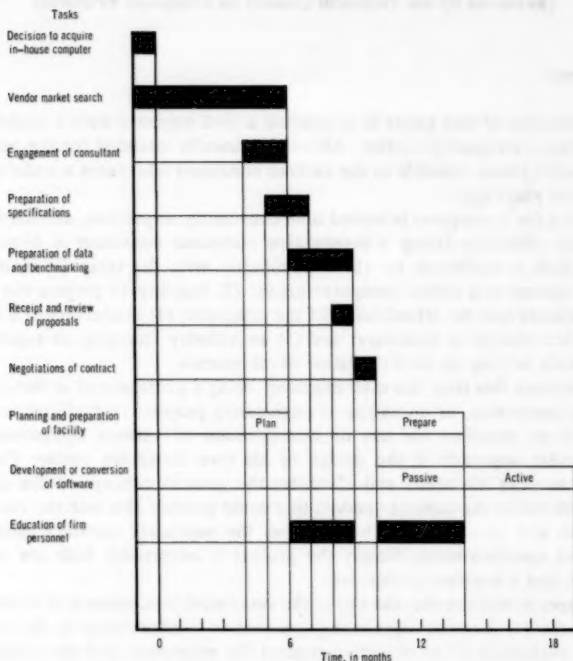


FIG. 1.—Tasks and Duration of Computer Acquisition (Duration Shown is Exemplary)

sophisticated software enables the extension of computer services to word processing and information management, thus increasing the capability and usage of computers. Justifying an in-house computer center should be based upon proper financial analysis reflecting all financial considerations and technical attributes. In searching for a new computer consideration should be given to the acquisition of a demonstrator or used but not antiquated computer which

may be bought for relatively low prices. Since their supply is not ample, the decision must be made quickly when the opportunity appears.

**First Purchase.**—It is assumed that the first-time computer consumer has worked with computers, is satisfied with the results, and is now ready to acquire a computer. The justification is dependent upon financial considerations and expediency. The total cost of a service bureau use is represented by the cost of computer central processing unit (CPU), input/output (I/O) and connect time, data storage rental, telephone lines and terminals or personnel travel to and from the service bureau, or both. In addition, if a company does not have its own computer facilities, most often it will not have software development capabilities and it will have to depend upon the service bureau. Therefore, the cost of these services must also be included. Expediency refers to the total turn-around time which affects production and cost.

A rule of thumb to follow is that if the average monthly expenditure for the service bureau exceeds 75% of the monthly rental or lease of an appropriate in-house computer, the decision should favor the establishment of a computer center. Although present day minicomputers are minis only with respect to price and not to performance, there are large software that require large mainframes. If the user needs such large software then the percentage would very easily increase. In such cases consideration should be given to establishing a small in-house computer center with the ability to communicate with a service bureau for the use of the large programs.

**Existing Computer Replacement.**—A considerable number of civil engineers had the foresight and the ability to establish an in-house computer center long ago. However, new developments in the electronics industry have made many of those computers obsolete. These engineers, if they can justify their existing systems, can justify a replacement.

The major argument against a system change is the expense of program conversion. However, compared to the costs of updating old software and developing new software, the benefits of increased performance and reduced cost per computation may indicate a favorable return over a period of 5 yr-7 yr.

In order to justify a computer, may it be the first or a replacement, the engineer must: (1) Identify his present situation; (2) determine, to the best of his ability, his objectives; (3) define his computing needs; and (4) plan a program of computer solicitation in an organized and thorough manner.

#### **VENDOR RESEARCH**

While preparing the financial analysis, the consumer must learn about the general inner workings of the computer and define his needs. Concurrently he must survey the market and determine which vendors can meet his general needs.

**Hardware Needs.**—The specific needs of a user can be determined only after a careful review of the user's computer applications, volume, and method of operation. Some general guidelines are given below:

1. **Processing.**—Batch mode processing is desirable for high volume production. However, interactive processing enhances engineering, promotes computer

use, and reduces card and paper volumes and its related storage and waste needs. Many present day hardware can be operated in either mode.

2. Memory Size.—Memory size is one of the least expensive commodities of the computer industry. A memory size of 64 KB should be considered an absolute minimum.

3. Type of Memory.—In the years past, civil engineering programmers had become experts in shoehorning large programs into small memory size computers. Virtual memory now offers these programmers the benefits of "extended" memory at relative modest prices.

4. Multiprogramming.—When considering multiprogramming, it should be determined if the memory is partitioned, thus reducing the memory available to each user, and if so, whether it is done automatically by the computer or by the programmer, user, or operator. A true virtual memory computer has no partitions.

5. Auxiliary Memory.—The use of magnetic disks (fixed, interchangeable, floppy, etc.) is a *must*. The size and number of drives depends upon the user's needs. If considering the use of the computer as a word processor, a second drive may become important. A second drive will also prove valuable as a fast backup unit.

6. Magnetic Tape.—A magnetic tape drive is quite valuable for storing backup data, providing a high volume input/output medium, and for transferring programs between computers. Tapes usually have 7 tracks or 9 tracks (transversely) and densities of either 800 bits/in. or 1,600 bits/in. (longitudinally). Caution should be used in that other densities, even if not common, do exist. Tape drives are available with switch selectable densities. Tape drive speeds of 45 in./sec-75 in./sec are considered sufficient.

7. Card (I/O).—Card output should be discouraged. Magnetic media should be used machine readable for output. The cost of a card reader, however, is relatively inexpensive in comparison to the total cost of the computer and it is recommended (there are still many card punches around). A card reader could offer an inexpensive connection to a digitizer.

8. Printer.—A line printer with 132 columns, 64 characters, and a speed of 240 lines/min is reasonable for a mini or larger computer. Consideration should be given to upper and lower case because such a feature extends the application of the computer to word processing. Such a feature, however, costs more and slows down the printer speed by approximately 25% and may or may not be able to be field installed at a later date. Character printers are quite common in small computing systems or as terminals. Their speeds range from 30 cps (characters per second)-120 cps and their cost is a fraction of a line printer. Many character printers can print only 80 columns. Before deciding on such a printer, consideration should be given to the output formats of the software to be employed. One option to consider is the installation of a line printer without upper and lower case and a high quality character printer. The net increase in cost is minimal.

9. Terminals.—There is a multitude of terminals in a wide price range. Many have various text editing features that are not needed if the computer has a good operating system. Before acquiring a terminal, it should be tried out for the "feel." The cathode-ray terminal (CRT) is great, but consideration should be given to the ability of having a hard copy. This becomes quite important

if the computer line printer is distant from the terminal.

10. High Volume Data Key Entry.—Not all operations lend themselves to interactive processing. Therefore, there should be available the old faithful keypunch another device (diskette, floppy disk, cartridge, key to disk, etc.) or on-line data entry to record input.

11. Other Peripherals.—The pen plotter has found extensive uses in civil engineering, but its need and selection is not considered here. Those, however, who are replacing an existing system that has a pen plotter should determine whether the plotter can be attached to the new computer directly or whether it will require an interface. The same applies to any other peripheral hardware.

12. Software Needs.—The operating system (the heart and brain of the computer) and software such as FORTRAN and other compilers, applications programs, as well as user's groups, are equal to, if not more important than, the hardware. The engineer should prepare a questionnaire which should be formally completed by each vendor and confirmed by users of the vendor's equipment. The reader is referred to the questionnaire paragraph of the proposal section.

13. Vendor Market.—To determine the potential market, the engineer has at his disposal a multitude of free publications in which vendors advertise and which carry articles on the features and performance of various equipment. There are also publishers who compile and sell reports on vendors and their products. The names of these publishers are advertised in almost all trade journals.

The consumer may consider hiring a specialized consultant to assist him in the selection of the computer. Such a consultant should be familiar with civil engineering work and preferably be a civil engineer. Attending conferences, especially computer trade shows, will prove invaluable. The consumer should also contact his colleagues that have previously purchased a computer or are currently in the process. Once a vendor search has begun, the prospective buyer will be surprised how rapidly various vendors will emerge.

The search will require the investment of time and money. This necessary investment, however, is quite small, when compared to the total cost. During the vendor search and subsequent negotiations, it is important to maintain an open and impartial mind and to avoid any friendships or personality clashes with the vendor representatives.

#### REQUESTS FOR PROPOSALS

The engineer, having consulted with the vendors and drawn from them useful information, is now in a position to actively solidify his plans and request proposals. In this phase the engineer is faced with four activities: (1) Preparation of specifications; (2) advertisement; (3) benchmarking; and (4) education.

**Specifications.**—Preparing specifications for the acquisition of a computer is not any different than writing specifications for a design project. One will be surprised how much is learned about the needs of the computing center and the company by undertaking the specification writing. In addition, this activity will facilitate the selection process, reduce the barrage of telephone calls from vendors, and will eliminate vendors that cannot provide the necessary products. The extent and complexity of the specifications depend upon the size of the

proposed computing system. The general scope, however, is basically the same. The specifications should be divided into general sections similar to engineering specifications.

The Introduction should state the Engineer's background in electronic computing, intended use of the computing system, integration of the computer center within the overall company structure, computer strong points and weaknesses, method of operation (batch or interactive), type of shop (open or closed), duration of service, i.e., one shift, two shifts, or three shifts, and any other information that may assist a vendor in the submission of an appropriate proposal. A general description of any existing major programs and their application is appropriate.

**Information to Bidders.**—Under this section, the engineer should include his instructions to the vendors containing at least the following:

1. Due date of the proposals, date by which the engineer expects to reach a decision, and expected date of system delivery.
2. Format of the proposal.
3. Description of any options to be considered. Provision should be made to encourage vendors to propose alternate options that in his opinion would improve the system.
4. Method of Selection.—It should be brought to the attention of the vendors that price alone will not be the sole criterion for selection. Of utmost importance is the: (1) Overall system performance as verified by references, including those submitted by the vendor; (2) vendor financial stability; (3) vendor's support of users of his equipment; (4) system software performance; (5) availability of applications software either through the vendor or the open market; (6) ability to easily upgrade the system hardware without reprogramming; (7) long down time; (8) obsolescence of peripheral equipment; and (9) proximity to the installation of the vendor's service center. It should be ascertained whether the service will be offered by the vendor or by a third party. It should be made clear that the engineer reserves the right to make his selection of his own will and judgement, and that he offers no definite basis whatsoever upon which he will base his selection.
5. Benchmarking requirements and availability, at no cost, of a system for conversion and testing until the system's delivery.
6. Request for at least five references of installations with the same equipment as proposed and preferably with similar interests or applications as the engineer and as near to the engineer's site as possible.
7. Job accounting requirements.—For internal (intercompany) or external (client) reasons the engineer will usually want to keep track of processing time and use of system resources. Possible requirements could be the ability of the computer to account for any or all of the following: (1) CPU time; (2) disk I/O time; (3) printer line count; (4) core blocks used; (5) terminal connect time; (6) file storage; and (7) plotter usage. The accounting could be made by any or all of the following: (1) User number; (2) project number; (3) program name; and (4) data and time. It will be preferable if the vendor could avail a general job accounting software package which the engineer can tailor to his needs. Most vendors, however, offer most of the aforementioned requirements as a function of their operating system. The user has the ability to access this information, but must do it on his own.

8. **Definitions.**—Abbreviations, colloquialisms, short descriptions, and such words as the *vendor*, the *engineer*, the *owner*, the *system* and the like should be defined at the very beginning of the specifications. Since the vendors are given some latitude in the specification requirements or conditions, they should be advised which conditions *must* be fulfilled, which are *required*, but if not delivered the vendor will be penalized but not eliminated, and which are *requested*, but if not provided will carry no penalty.

**Vendor Financial Status.**—Construction specifications require a bid bond and a performance bond from prospective bidders. No computer vendor will consent to such a request; many, however, will be happy to submit their corporate statements as evidence of growth and strength.

**Performance Specifications.**—These should describe the desired features of each of the hardware units being solicited, and of the system and application software desired. It is questionable whether a detailed technical description of every feature or component is really necessary, if not impossible. With respect to memory and for common comparison, the following should be requested: (1) Basic size; (2) increment size; and (3) available memory to the user excluding the operating system.

**Proposal.**—This may be a simple table listing the various items, quantities desired, unit and total purchase cost, and monthly maintenance charge. If any options are to be requested, they should be identified in this table for easy bid analysis. A summary sheet of the base bid and options is advisable. Also desirable is the cost of rental, lease, and lease/purchase options if available through the vendor.

As part of this section the vendor should attach a copy of his standard purchase, rental, lease, or lease/purchase agreement(s) and the same for his maintenance agreement.

**Questionnaire.**—This should be designed to obtain the vendor's formal reply to such items as:

1. FORTRAN conformance with ANSI (American National Standards Institute) standards, deviations thereof, level of sophistication, and optimization of user code.
2. Vendor's knowledge of differences between his FORTRAN and that of the engineer's, if the engineer presently has computing capabilities, and that of other vendors which may hinder program portability. Features to be aware of include: (1) Division by zero; (2) I/O statements; (3) file handling, (4) free form I/O ability; (5) plotter subroutines; and (6) other features.
3. Size of the operating system and other overhead on memory.
4. Handling of oversized programs.
5. Method of memory partitioning (automatic or operator controlled) for multiprocessing.
6. Availability of virtual memory (some vendors have hardware that can accommodate virtual memory but their operating systems cannot).
7. Text editing of input data and files and availability of special features for use in word processing.
8. Method of file security.
9. Hardware/software limitations and ultimate limits of expansion.

10. Existence and support of users group, extent of group program library, and method of program acquisition or exchange.

11. Compatibility with equipment presently owned by the engineer such as plotters, digitizers, terminals, etc.

12. Availability of general application software such as sort-merge, data base managements, plotter routines, commercial subroutines, statistical subroutines, and other compilers such as RPG, COBOL, etc.

13. Availability of application programs of specific use to the engineer.

14. Provisions for education of the engineer's computer center staff and cost thereof, if any.

**Advertisement.**—With the specifications completed the engineer is now in a position to solicit proposals. Notice should be taken that the word "bid" has not been used since this word implies that the lowest quote will be awarded the contract. Experience has shown that a negotiated contract can generally produce a lower price for the desired work or product. Advertisement of the proposal in trade publications is not considered as necessary. The market research phase has identified numerous possible vendors. Therefore, a letter of transmittal accompanying a set of the specifications plus, perhaps, a telephone call, should suffice.

In many engineering projects it is considered prudent to hold a "pre-bid" or "pre-proposal" conference in which the prospective contractors, having read the specifications, meet jointly with the owner and the owner's engineer to clarify any questionable items of the plans and specifications. A similar conference could be held by the engineer and his consultant, if any, with the prospective computer vendors. The main objectives of such a conference should be to:

1. Explain the needs of the engineer.
2. Review the specifications and correct any ambiguities.
3. Establish commonalities between the vendors so that a just judgement will be made during the proposal review.
4. Attempt to draw the vendors into a competition that will yield the most appropriate configuration for the price that is considered affordable.

**Benchmarking.**—One of the most important yet somewhat difficult facets of computer selection is the benchmarking of the proposed hardware. Each vendor will quote benchmarks performed on his hardware and compare them with his competition. These benchmarks, however, represent strictly arithmetic calculations and they often do not represent a true model of the engineer's computational environment. To create such a model is time consuming and therefore expensive. Many vendors will be reluctant to invest the necessary amount of time to convert, let alone develop, the desired program. Therefore, the engineer should provide his own benchmark. In doing so, he should exercise care in selecting one or two programs and convert them into each vendor's machine requirements. If the engineer undertakes this task, the vendors should be pleased to process them. It is advisable that the engineer be present when these benchmarks are run so as to get a first-hand experience. Consulting with fellow colleagues that may have similar experiences is a must.

The engineer that is replacing an existing computing system should be careful of emulators and should determine their full implications. To be considered

are the effects upon program performance when running under an emulation mode and the effort necessary to run under the vendor's own unemulated system software.

**Education.**—Most vendors offer educational seminars in the use of their equipment. It is ideal if the engineer could attend such a seminar, sponsored by each vendor, at this stage prior to final selection of the equipment. Such seminars will offer invaluable input in the selection process.

#### **VENDOR SELECTION**

The evaluation of the proposals received may be a rather difficult task because of the: (1) Presence of a multitude of criteria with varied weights of importance; (2) submission of alternative options; and (3) resistance of vendors to follow the requested proposal format.

**Spread Sheet.**—Just like in any construction project bid evaluation, the engineer should prepare a spread sheet which will compare the various proposals.

**Selection Process.**—The selection process involves the analysis of the spread sheet, the results of the benchmarking, the educational knowledge gained, the investigation of the vendor's local service and general support, and on the personal interviews with the vendor's and the user's colleagues. Prior to the final decision it is recommended that a personal interview be held with each vendor to ascertain the explicit interpretation of the proposal.

All proposals should be ranked by taking into account: (1) Machine performance; (2) applications, software availability and conversion effort; (3) maintenance; (4) vendor credibility; and (5) life-cycle cost. Life-cycle cost should include the costs of: (1) Hardware; (2) interest; (3) maintenance service; (4) purchased software; (5) conversion of existing applications software; and (6) any other operational costs that may differ between the various proposals.

An equally important consideration is the availability of a system and time for backup processing at another site in case of equipment breakdown for an extended period. In evaluating such a site, machine and operating system compatibility, proximity to the engineer's location, time of backup availability, and cost of such backup processing should be considered.

Prior to reaching final decision on the ranking order, it is recommended that the engineer contacts the various references the vendors listed and the other users of the vendor's equipment. Reference contact by letter is inexpensive, but cumbersome, time consuming, an imposition, and does not guarantee an honest, or in fact any, reply. Telephone conversation is by far the least expensive, but does not offer a personal contact. Needless to say, a personal visit to a site will allow one to see, hear, and feel a user's reaction to a vendor and his equipment. In receiving the answers to questions pertaining to satisfaction with a vendor, one should pay close attention to the content of the reply and connotation of the words used, and observe the eye expression and enthusiasm with which the reply is being given. Many times a user will not criticize a vendor because he depends on the vendor for service and support or because pride does not permit him to admit he made a bad decision. In seeking information the engineer should converse not only with the management but also with the engineers who use the computing system and with the computer center staff. In general, the questions asked should include: (1) Satisfaction and reason with

the vendor's equipment, maintenance service, software, and support thereof; and (2) identification of any problems, the vendor's ability to solve these problems, the magnitude of down time and recommendations or suggestions.

Having ranked the proposals, the engineer may create a short list of a few vendors, inform them that they have been "shortlisted," and inquire whether any additional information could be provided in their further competition. Such further information could possibly yield a reduction in cost, or the gratuitous inclusion of some "freebies" or other amenities.

From this point negotiations should commence with the highest ranked vendor. If negotiations cannot come to a fruitful conclusion, they should then be terminated and negotiations should begin with the next ranked vendor and so on.

## CONTRACT NEGOTIATION

Public-works projects are easy to award. The lowest qualified bidder always gets the contract. Public-works projects, however, do not always yield the best price for the work received. Therefore, the engineer should be prepared to negotiate for the price and for the terms of the contract; for this he may consider the engagement of the services of an engineer with expertise in hardware and software.

**Price Negotiation.**—Engineers are accustomed to contract negotiations from the other side of the fence. As professionals they are supposed to propose fees for services offered. If the prospective client wants to cut costs the engineer reduces services. In the case of computer selection, however, it is unfortunate that, generally, the price quoted is an inflated or list price. The computer vendor is aware, and if not, he should be informed that if he does not "do better," the next vendor in line will get the contract. Therefore, an off-the-list-price reduction of 10%–25% may not be too far out of line. But, not all vendors are like this. Some of the big and more established firms have fixed prices and a "take it or leave it" attitude. Since the act of negotiation is intermixed with the condition of the market and personalities, no attempt will be made.

**Contract Terms Negotiation.**—Unless the engineer can develop clout over the vendor he is fairly much locked into the vendor's standard form of contract which protects the vendor. There is, however, room for negotiation on certain terms. Since this negotiation involves a legal document, it is highly desirable for the engineer to seek legal advice.

The contract addresses two major concerns, the goods and the method of payment. Pertaining to these are the following typical common clauses:

1. **Warranties.**—The vendor will generally warrant that his equipment will be free of defects and that he will make necessary repairs for a period (usually three months) at no cost to the engineer for labor or parts. The vendor will not express or imply any warranties as to the merchantability or fitness for a particular use. Furthermore, the vendor will want the engineer to acknowledge that he, the engineer, has made the selection of all equipment based solely upon his own judgement. To this, the engineer should take exception and insist that a clause be included which states that the equipment is in conformance with the engineer's specifications and with all statements made by the vendor in his proposal to the engineer.

Usually the vendor will demand full payment or the payment of the first installment upon signing of the acceptance receipt. This receipt says that the equipment has been delivered and installed. The engineer should note that the vendor's claims of operable equipment in a matter of hours or a day or two are just dreams or promises. Therefore, the engineer should not sign such a receipt and it is recommended that a clause be included in the contract stating that such receipt will not be signed until the entire computing system (hardware and software) is operable for a period of 30 days with a down-time rate of less than 5%. Downtime should be defined as the number of inoperable hours divided by the total scheduled or anticipated hours in percent form.

2. Maintenance.—In addition to the acquisition agreement, the engineer will have to execute a separate agreement on the maintenance of the equipment. Therefore, if both agreements are not executed concurrently, the purchase or lease agreement should be subject to the engineer's acceptance of the maintenance agreement. These two agreements should be tied together by cross referencing of clauses so that nothing in one agreement will negate anything in the other. Redundancies and clauses of similar wording should be avoided. Maintenance agreements are usually renewable each year unless they contain an automatic extension.

The maintenance service and its agreement are extremely important. Therefore, the vendor should fully describe the extent of service, the hours and days of service, the response-to-call time, and any causes for additional charges. Unless the engineer expects to use the computer on a regular extended time schedule, a 24-h, 7-day service coverage is not deemed necessary. Of particular importance is the case where equipment from more than one vendor is installed. Therefore, it also behooves the engineer to have a one-call-one-service maintenance contract.

Usually the monthly cost of a maintenance agreement ranges between 0.7% and 1.0% of the purchase price. Many vendors, in addition to hardware maintenance, have software maintenance beyond the first year. Under this maintenance the user receives all modifications and updates to the purchased software.

3. Delivery.—The vendor should specify a date of delivery. The expected duration of installation should also be specified. It should be ascertained whether the cost of installation is included in the price quote or not. If the engineer is replacing an existing computer which he has been committed to evacuate by a set date, he should consider the incorporation of a clause in the contract which commits the vendor to a computer start-up date and enables the engineer to recover costs if such a date is not met. Of course the due date should be reasonable and the costs realistic and not punitive.

It is to the engineer's advantage that the equipment be delivered by the vendor to the actual computer quarters (address and floor) and that freight insurance be arranged by the vendor. For this, an additional charge will have to be underwritten by the engineer.

4. Tax Investment Credit.—The engineer should ascertain that this credit be passed onto him by the vendor.

**To Purchase or Not.**—Basically there are three ways to acquire a computer purchase, lease/purchase, or rent. When purchasing, the engineer buys the

items he needs outright and arranges for his own financing.

Under a lease/purchase agreement, the engineer leases the machine for a specified period at the end of which he exercises an option to buy the equipment for a pre-agreed price. This seems to be the most favored method. The period usually ranges from 3 yr-7 yr with 5 yr often being the optimum, taking into consideration total interest paid, monthly payments, and obsolescence of equipment. The option to buy is negotiable. Most vendors will want this price to be 10% of the original quote. Third party lessors may have as low a price as one dollar.

Renting usually with 3 month-12 month cancellation notice, is discouraged by all, because of its high cost, and some vendors do not offer it at all.

The engineer should review these methods with his financial advisors and decide accordingly, taking into account amortization, overhead, and cost recovery. When negotiating for a lease, may it be through the vendor or a third party, the engineer should pre-agree with the lessor on early agreement termination penalties.

#### PREPARATION FOR NEW ARRIVAL

Fig. 1 indicates that the physical planning and preparation of the facility for the new arrival must commence early in the process of the computer acquisition. Four major areas are to be identified in this phase: (1) Education; (2) software; (3) quarters; and (4) operation. Education addresses the acquaintance of the personnel with the expected computer and electronic computing in general. Software refers to the task of developing, converting, or somehow securing the required programs needed to get the engineer started. Quarters pertains to the physical planning and preparation of the room or office space which will house the computer and support staff. Operations include the establishment of rules and procedures for operating and managing the computer center. Be the engineer a neophyte or an old battle scarred veteran, consultation with others with similar experiences is highly recommended.

**Education.**—The number of people trained depends on the size of the engineer's firm and its commitment to the computing center. It would be beneficial, however, if at least two members of the staff become knowledgeable. The quality of education varies from vendor to vendor and usually a 1 week seminar does not prove adequate for one to become proficient. Therefore, it is suggested that arrangements be made with the vendor to gain access to a machine, prior to computer delivery, so that the trainees can keep in touch with the system and at the same time be able to do actual program development or conversion.

**Software Development.**—The development of good software requires sound engineering judgement, good programming knowledge, and sufficient amount of experience. The first requirement is assumed as given and available to the engineer. The second may be acquired by hiring an experienced programmer. However, experience of the firm, and not of the programmer alone, takes time and costs money. In the early years of the computer revolution engineers had no choice but to develop their own programs. Soon they discovered that collaboration expedited progress and reduced work so various user groups were formed. Today it is totally unnecessary for a newcomer to the field of electronic computing to reinvent the wheel and do it alone. There are many engineers

that are willing to sell certain software to help recover some of their costs. In addition, there are engineers specialized in software development that offer their services for just that purpose. One thing to remember is that in order to develop a decent size program the engineer will have to devote at least 1 man week-2 man weeks just to the preliminary or conceptual stages of program development. Taking into consideration all related personnel costs one will find that in many instances it does pay to purchase a program. But, in purchasing a program it may not necessarily mean that such a program will totally satisfy the engineer. Modifications and special tailoring will most probably have to be made. This is the benefit of progress.

Program conversion can be time consuming, costly, aggravating, and painful. Program conversion is a necessary evil and a fee one must pay to achieve the ultimate goal of success. In order to prevent this horrendous task from becoming a nightmare, a systematic process must be undertaken. First, as a result of the education received, the engineer should identify all differences between the old and new computer languages. Particular attention should be paid to those differences caused by deviations from standards. This is particularly evident in older machines and in some vendors. Second, the engineer should identify these deviations in all programs to be converted. Of particular importance, is the file handling, division by zero, and radicals of negative numbers. Third, before proceeding with the conversion, attempts should be made to locate any conversion aids or translators developed by others. If these attempts fail, consideration should be given to developing one in-house. Many times a vendor may recognize the marketability or promotional value of such a translator and may decide to assist in the development.

Having established the mechanics of the conversion process, the engineer must manage the actual efforts in accordance with a predetermined time schedule and in a manner similar to an engineering project. Prior to conversion each program must be reviewed with the principals and the engineering staff to determine: (1) Continued need of the program; (2) necessity of any basic revisions; (3) additions or deletions; and (4) priorities.

**Site Preparation.**—Having ordered the computer it is time to implement the planning of the preceding months. Quarters will have to be secured to house the new equipment. The customer engineer of the vendor should be contacted to assist in this preparation by planning for floor layout, power requirements and appropriate receptacles, air conditioning, and access of the equipment into the proposed quarters. At the same time consideration should be given to the location of the support staff, supply storage, and data storage. Site planning is not considered as part of this paper.

**Operations.**—Although not a part of the intent of this paper the reader is alerted that now is the time for the engineer to consider the methods of computer operations and its management.

#### SUMMARY

The acquisition of a computer represents a financial investment and a task that requires a formal approach which includes: (1) Sound engineering investigation, evaluation and preparation; and (2) sound business justification, contract negotiation and financing.

General guidelines, treating computer acquisition as an engineering project, have been presented for adaptation to prospective consumer's needs.

#### ACKNOWLEDGMENTS

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#### APPENDIX I.—GLOSSARY OF TERMS

**Algorithm.**—a set of rules and procedures to follow in order to solve a problem. An example would be the procedure and calculations one follows in carrying out long hand division.

**Benchmarking.**—the process used to evaluate the performance of different computers relative to one another and to preselected criteria. A problem input to a computer program for calculation of computer output to compare with known results or other accepted similar results.

**Bit.**—an abbreviation of binary digit.

**Byte.**—a group of adjacent binary digits (bits) forming a subunit of information. In many computers, the byte is the standard of measure of the computer's memory size.

**COBOL.**—Common Business Oriented Language. A computer compiler which allows a programmer to write application software intended for the business market rather than for engineering or science.

**COMMON.**—a FORTRAN command which allocates the same computer memory location to certain variables of different, but interrelated, software.

**Compiler.**—a computer program that prepares a machine language program from instructions (commands) written in another language such as FORTRAN.

**Computer Aided Solution (to an engineering problem).**—the use of computer programs and computer output to aid an engineer in his work (generally analysis or design/code checking).

**Computer Services.**—expertise provided to operate a computer, to process computer applications, or develop or support application software in-house or at a service bureau, or both.

**Computer Solution.**—calculations performed by a computer program.

**Configuration.**—the specific set of equipment connected together to form a single computing system.

**CPU.**—Central Processing Unit. The part of the computing system that contains the circuits which control the interpretation and execution of instructions, including the necessary arithmetic, logic, and control circuits to execute the instructions. The CPU includes five units, namely, the control, the arithmetic, the memory, the input, and the output.

**CRT.**—an abbreviation for cathode-ray tube. A television like tube used as a terminal to communicate (input data and display output) directly with a computer.

**Data Processing Techniques.**—Techniques for solving problems which utilize computer programs as essential parts.

**Data Storage Charge.**—the charge levied by a service bureau for keeping user data or software on magnetic disks, tapes, and other media.

**Echo-Printout.**—the printing by the computer of the data used as input to a computer program.

**File.**—a collection of related records of information pertaining to data or software.

**FORTRAN.**—Formula Translator. A computer language designed to instruct computers to execute algebraic problems.

**Hardware.**—the physical components that comprise a computer and its peripherals.

**Host Computer.**—a computer with which terminals and other (generally smaller) computers communicate.

**I/O.**—Input/Output.

**In-House Computer.**—a computer which is totally owned or leased by the engineering firm which uses it.

**In-House Software.**—computer programs which are totally controlled by the engineering firm which uses them. These programs may have originally been developed by others or they may have been written by engineers in the firm.

**Input.**—data that is to be processed by a computer.

**Kb.**—1,000 bytes.

**Key Entry.**—the entry of information into a computer by means of a device having keys (keyboard).

**Language.**—a set of representations, conventions, and associated rules used to convey information.

**Language, Machine.**—a language used directly by the computer.

**Language, Problem Oriented.**—a language which allows the user to communicate with the computer in terms or commands applicable to the user's application.

**Main Frame.**—generally the CPU of a large computer.

**Memory.**—a component unit of a CPU where information can be stored.

**Minicomputer.**—originally referring to small specialized computers, minicomputers have become quite powerful and approach many main-frames in speed, memory, and overall capabilities.

**Modeling Techniques.**—procedures for reducing a given physical situation into the parameters or input data of a computer program.

**Multiprocessing.**—the simultaneous processing of two or more programs by one computer.

**Output.**—printed listings of the information which has been input to a computer or of the results of calculations performed by a computer. Also sometimes refers to graphical information or displays which are created by a computer program and drawn by a plotter or displayed on a TV-like screen.

**Out-of-House Services.**—use of computer programs purchased from a company or person outside the engineering firm, most often from a service bureau. Also sometimes refers to computer programs which are licensed from service bureaus, quasi-governmental units, or others, and run on an in-house computer or at another (or the same service bureau).

**Peripherals.**—specific devices or equipment associated with a computer. On-line peripherals are connected to the CPU. Off-line peripherals are stand-alone units.

**POL.**—See language, problem oriented.

**Portability.**—the ease with which a program developed on one computer type can be used on another computer type.

**Processing, Batch.**—the processing of data prepared separately from a computer, e.g., preparing the data for an application program, submitting it to the computer center for processing, and then receiving the results.

**Processing, Interactive.**—the processing of data on an interactive mode with a computer; the user has direct communication with the computer.

**Program.**—a set of instructions for a computer's calculations which describes an algorithm.

**Programming.**—the activity of writing a computer program.

**Public Domain Program.**—a computer program which is distributed without any restrictions on how it may be used. Public domain programs are often developed by governmental agencies or academic institutions and distributed by providing copies for a nominal charge to cover the costs of reproduction.

**RPG.**—Report Program Generator. A computer language used primarily for business applications and generation of reports.

**Security.**—the methodology, techniques, or procedures used to secure the hardware and software against vandalism, fire, theft, and other destructive actions may they be accidental or premeditated.

**Service Bureau.**—an organization which supplies computer services. These services generally include providing the use of computer programs run on computers at the service bureau, license of computer programs to run on the customer's in-house computer, the use of a computer, or the provision of computer specialists to write programs or assist in modeling.

**Software.**—instructions, data, and information necessary to operate the hardware of a computing system. Synonymous to computer program.

**Software, Application.**—software used for a specific problem or application such as coordinate geometry, structural analysis, water distribution, river modeling, payroll, etc.

Software, System.—software essential to the operating or functioning of the computing system and of general objectives as compared to applications software.

System, Computing.—the combination of software and hardware used in computing operations.

System, Operating.—the totality of systems software necessary to operate a computer.

Terminal.—a unit used to communicate with a computer.

Time, CPU.—the time expended by a CPU to process a program.

Time, Connect.—the duration of time that a terminal is communicating with a CPU. Beginning to end of remote processing. Always greater than the CPU time.

Time, Disk I/O.—the time spent to transfer information between a disk and the CPU.

Time, Down.—the time a computer is in-operable due to a fault or failure.

Time Sharing.—to make the time of a device available to two or more programs.

Time, Turn-Around.—the total time of submitting input for processing and receiving the results (output).

User Group.—a group of computer users of common interests organized for the purpose of exchanging information and or software. Software exchange need not be free.

Word.—a group of characters treated as a unit and to which meaning can be attached. A word may be comprised of two or more bytes. Also a measure of computer memory size.

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# JOURNAL OF THE TECHNICAL COUNCILS OF ASCE

## LOW COST SEISMIC STRENGTHENING OF POWER SYSTEM<sup>a</sup>

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(Reviewed the Technical Council on Lifeline Earthquake Engineering)

### INTRODUCTION

Strong earthquakes damage weak structures. Well-built structures survive. But how strong does a structure have to be? How much additional expense, beyond conventional construction costs, can justifiably be devoted to enhancing seismic resistance?

In a high seismicity region a cost increase of a few percent can provide adequate seismic resistance. In a region of low or moderate seismicity, however, earthquake probabilities are so low that the increase of construction cost which can be justified is almost nil. Nevertheless, even in cases of no economic justification, inexpensive measures which would enhance seismic resistance should be adopted, as a matter of conscience.

Examination of what earthquakes have actually done to electric power systems over the last few decades provides the basis for suggestions of low cost measures that could prevent damage in future seismic events.

### EFFECTS OF EARTHQUAKES

**Hydroelectric Power Plants.**—In earthquakes in Alaska 1964, Kern County 1952, and Kanto (Japan) 1923, penstocks and canals were broken and damaging landslides occurred. Of 91 hydroelectric plants in the Kanto area, 23 were damaged. Turbines have been endangered by rocks and soil masses entering the water system in Alaska 1964 and Kern County 1952. Dams may be endangered, as in San Fernando 1971.

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**Thermal Power Plants.**—Seismic stops (or thermal expansion guides) on boilers were overloaded and deformed in the Niigata 1964 and the Imperial Valley 1979 earthquakes. The Miyagi 1978 event caused internal damage to two large boilers; tubes broke and connections cracked.

When a generating station loses power, the turbines must be lubricated while running down, and turning gear must be powered in order to allow the shaft to cool without developing a bow. In the Miyagi 1978 and Kern County 1952 earthquakes, shaft and bearing damage resulted from a lack of sufficient emergency station power.

Station batteries needed for controls, lube pumps, and to start emergency generators, may be damaged by falling from, or overturning, their racks. This happened in the Long Beach 1933, San Fernando 1971, and Miyagi 1978 events.

Computer cabinets may fall over or drop a leg into cable holes in the raised (pedestal) floor as in Miyagi 1978. Control cabinets and communication equipment racks may fall over or be deformed as in San Fernando 1971.

In the Kern County 1952 earthquake, the thrust bearing of one of the station power turbines burned out.

In the Imperial Valley 1979 event, a feedwater heater skidded sideways at the expansion support, due to lack of lateral restraint.

Also in Imperial Valley 1979, anchor bolts of the gunite-lined steel stacks pulled out a few millimeters due to rocking of the stacks. In the Long Beach 1933 event, a concrete stack supported on a steel frame cracked severely and the frame was deformed.

In some cases, such as Imperial Valley 1979, the boiler pounds against the turbine building operating floor. In Managua 1972 and Guatemala 1976, the turbine building operating floor pounded against the turbine support; this severely damaged the turbine-generator.

In the Imperial Valley 1979 event, forced draft cooling tower damage occurred: bolted connections pulled apart and column base plates crushed. (This happened in an old tower and was due to deterioration of the wood.) Fan blades and gear boxes were damaged in Kern County 1952 due to blades impinging on the fan housing.

Oil storage tanks have been damaged in many earthquakes: Alaska 1964, Niigata 1964, Miyagi 1978, and Kern County 1952. Buckling of the wall may occur, often as an "elephant's foot." The floor plate may rupture at a hard point such as a pipe connection or a roof support. Roof structure, guides and seals may be damaged by sloshing. If a tank wall ruptures and dumps the contents rapidly, the shell may collapse implosively due to inadequate vents in the roof. In the Niigata 1964 and Miyagi 1978 events, the retention walls were not able to contain all of the oil which spilled from damaged tanks, so fire hazards were aggravated.

**Transmission Systems.**—In almost every strongly felt earthquake, sudden pressure relays on transformers actuate (probably due to oil sloshing) and trip the circuit breakers. Usually this interrupts the circuit only momentarily and may do more good than harm in protecting slapping conductors from burning.

Transformers which are unanchored, or insufficiently tied down, slide, roll or bounce off their rails or foundation pads. If lucky enough to remain upright, they may survive with only bushing damage or broken lightning arresters. If they fall over they sustain major damage. Long Beach 1933, Puget Sound 1949,

Kern County 1952, Chile 1960, and San Fernando 1971, were all characterized by transformer anchorage failures.

Live tank circuit breakers, which have interrupter heads supported on porcelain columns, with or without porcelain tension guys, are particularly vulnerable to seismic shaking, as was evidenced in Miyagi 1978, San Fernando 1971, Chile 1971, Turkey 1967, and Chile 1965.

Dead tank circuit breakers (oil- or gas-filled) are less vulnerable. However, their bushings are massive and therefore susceptible to breakage, especially if jerked by connections to adjacent equipment. Usually the base skid of a dead tank breaker is bolted to the foundation pad with clips. In San Fernando 1971 some clips gave way, and in other earthquakes they have loosened.

Disconnect switches are generally resistant to damage. At Las Positas Substation in the Greenville-Livermore 1980 earthquake, vertical-break disconnect switches were shaken into misalignment (and arcing) due to inelastic bending of thermal expansion straps. Side-break switches at the same substation were not damaged. In the San Fernando 1971 event, at heavily damaged Sylmar Converter Station, four disconnect switches were damaged due to jerking of adjacent equipment. Two disconnect switches shook into misalignment and two insulators in these switches broke.

In the Chile 1965 earthquake, at heavily damaged San Pedro Substation where MMI IX was reported, vertical-break switches on steel lattice structures and side-break switches on separate supports were undamaged.

At Nishi Sendai Substation in the Miyagi 1978 earthquake, all 26 of the 66 kV switches were wrecked but damage to the 154-kV and 275-kV switches was less severe. The reasons for this difference are not known but may involve spacing or manner of interconnection with adjacent equipment.

In the Greenville-Livermore 1980 earthquake, two 230-kV oil-filled circuit breakers of a type which has unusually large clearances in the moving mechanism suffered broken guides and contacts, internally. Apparently this was due to being strongly shaken while tripping and reclosing.

The hydrogen-cooling system of two turbine-generator units at El Centro Power Plant was damaged, in the Imperial Valley 1979 event, due to broken pipe connections and pipes weakened by the corrosive content of locally-available water.

In the Puget Sound 1949 earthquake, synchronous condensers tripped due to shaking and some bearing damage resulted.

Lightning arresters, capacitors coupling potential devices, wave traps, and capacitor racks, are vulnerable either by amplification of ground shaking or by adjacent equipment falling on or jerking them. This was evidenced in Chile 1965, San Fernando 1971, Niigata 1964, and Miyagi 1978.

Transmission lines sometimes slap together, causing circuit breakers to open momentarily. Unlike distribution lines, transmission spans seldom get entangled and burn down. Such a burndown did, however, occur in the Kern County 1952 event in a 70 kV circuit.

Transmission towers are highly resistant to ground shaking but can be damaged by landslides, rockfalls, or failures of their foundations. This happened in Miyagi 1978, Alaska 1964, Niigata 1964, San Fernando 1971, and Kern County 1952. In the Kanto 1923 earthquake, 10% of the 2,400 transmission towers in the affected area were destroyed or damaged. In a few cases the damage involved

structural failure due to ground shaking, but most cases were due to landsliding or other foundation failures.

**Distribution Systems.**—Distribution systems are vulnerable in many of the same ways as transmission systems. In some ways the seismic problem is less severe because lower voltage equipment generally is less responsive to seismic ground shaking, having natural frequencies outside the range which has most of the earthquake's energy. On the other hand, some seismic problems are unique to the distribution system.

Because distribution conductors are closer to each other and on shorter spans than in transmission circuits, wrapping of conductors frequently occurs. The wires become entangled and may burn down before the circuit breakers sense that anything is amiss. This happened in Long Beach 1933, Kern County 1952, San Fernando 1971, Managua 1972, and Hawaii 1973, and probably in many other earthquakes where it wasn't reported.

Pole transformers are either bolted directly to the top of the pole or are supported on a platform between a pair of poles. In the Kern County 1952 event, about 850 platform-mounted poles fell over and most fell to the ground. It is remarkable that although 600 of those transformers were wrecked or severely damaged, only 50 suffered internal damage.

**Miscellaneous.**—Common to all parts of the system are failures of suspended ceilings; in several earthquakes this has been more a source of annoyance than danger. Other types of damage which bear mentioning are: collapse of battery rack or communication equipment rack, misalignment of microwave antenna, malfunction of emergency generator, collapse of shop buildings. In the San Fernando 1971 earthquake, spare parts which were needed for replacements were damaged by the earthquake and were unserviceable when needed.

## SUGGESTIONS

Reading the record of damage wrought by historic earthquakes brings to mind possibilities for preventing damage in the future. Some corrective measures are intuitively obvious, but some would require sophisticated analysis to determine what should be done. Some actions would be inexpensive and readily implemented while others would require major expenditures of effort and funds. In regions of high seismicity sophisticated analyses should perhaps be carried out, and where major expenditures would be cost-effective they should be considered. In low seismicity regions, however, too high a standard of seismic resistance is almost certainly a guarantee of getting nothing accomplished.

**Anchorage and Bracing.**—First and foremost, equipment should be anchored. Simple schemes for anchoring and bracing are better than elaborate ones because they are more likely to get implemented. Friction is not a reliable restraint to resist seismic vibrations although it may be helpful if sufficient clearance is available and if height-to-width ratio is not too great. Storage tanks for oil or water may be unanchored if height-diameter ratio is less than 1.5. Piping attached to the tank should have unsupported lengths long enough for flexibility to prevent damage when the tank rocks or slides.

Transformers should be welded to embedded steel in the foundation pad. Next best is to install expansion anchors in the concrete and bolt heavy clips over the skid base. Circuit breakers should be similarly anchored.

Pad-mounted customer transformers are not designed to anchor at base of the tank. To prevent damage, the tank can be hemmed in with shear bars at the edges and guyed by attaching threaded rods with turnbuckles to the lifting lugs at the top of the transformer tank. In high rise buildings such transformers are best placed in the basement. If the owner wants them high up in the building, effective anchorage becomes particularly important.

Pole transformers bolted directly to the pole have performed well in earthquakes. If mounted on a platform, shear bars or cleats at the bottom and close-fitted side rails above midheight will minimize damage.

Boiler support structures require substantial diagonal bracing or moment-resisting frames. Piping attached to the boiler should have sufficient flexibility so that relative motion between boiler and frame can be accommodated without damaging the pipes or their connections. Lateral restraints (seismic stops) to prevent excessive relative motions need not survive undamaged but should be able to distort severely when overloaded.

Feedwater heaters and similar horizontal tanks that undergo a wide temperature range always have one or more expansion supports on skids or rollers. Lateral motion should be prevented by using restraints with slotted holes that permit longitudinal motion only.

When designing anchor bolts for steel stacks or tall tanks, keep in mind that long bolts can stretch more readily than short bolts when subjected to the extreme overloads caused by seismic rocking. One way to cope with this is to provide strong mechanical anchorage deep in the foundation and have a weak bond between the bolt shank and concrete.

Computer cabinets can be internally damaged by pounding against adjacent equipment or overturning. Toggle bolts from the cabinet base to the solid deck below the pedestal floor provide cushioned anchorage. Tape reels should have a safety bar to prevent their being thrown out of their storage racks. Overhead pipes that might break and flood the computer should be reinforced or relocated.

Station batteries, which must be able to provide emergency station power, should be particularly well anchored and braced. Side rails are a necessity. Low profile racks are preferred. Not only should the racks be anchored to the floor but also they should be bolted back-to-back or to an adjacent sturdy wall if feasible. Resilient fillers between cells will prevent breakage due to pounding.

**Isolation.**—Rotating equipment is often mounted on vibration isolators to minimize transmission of noise. Such isolators amplify seismic inputs so the equipment tends to jump off the springs in an earthquake. If elimination of the isolators is not feasible, cushioned displacement limiters should be provided.

When laying out a substation, the designer should provide generous clearances to minimize the possibility that damage to one item will induce damage in another adjacent item. Also, interconnections should be slack enough so relative motion can occur without destructive jerking.

Fuel lines attached to emergency generators require flexibility to accommodate differential motion.

**Ceilings.**—Suspended ceilings should have diagonal as well as vertical supports. Light fixtures and other heavy devices should be firmly anchored to the ceiling framework or (better) independently attached to the floor above, with precautions to prevent (or allow for) relative movement between fixtures and ceiling.

**General.**—Electrical cabinets should have door latches that won't shake open. Mounting boards in electrical cabinets may need stiffening to avoid local amplification.

Spare equipment in switchyards or at material warehouses should be anchored or otherwise protected from falling or overturning when shaken. Heavy items should be stored on or near the ground. Shelving should be braced. Shelves should have raised front edges or heavy elastic cords parallel to the front edge to keep stored items from skidding or tipping off the shelves.

When selecting among different types of equipment and among different suppliers, keep seismic vulnerability in mind. High voltage equipment may be more susceptible to amplification of ground motion than lower voltage equipment, so precautions not necessary for the latter may be needed at higher voltage levels.

Threaded or clamped pipe connections are vulnerable to low-cycle fatigue failure.

Earthquake effects on a system may produce surprises. Repair crews will need fuel for their trucks, but the fuel pumps may be unusable for lack of power. Communication systems may be hampered by lack of power. Firefighting immediately after an earthquake may be difficult because of impeded access, broken water lines or damaged extinguishers. Chemical spills caused by an earthquake may be more difficult to cope with for similar reasons. Such unexpected combinations of circumstances should be thought of ahead of time and contingency plans made to prevent surprises.

#### SUMMARY

Anchor, brace, separate, guide, cushion, latch, limit, select, plan. With these key words as a basis, an electric power system's resistance to occasional strong earthquakes can be so improved that few post-earthquake explanations will have to be made. The power will stay on, or at least service will quickly be restored.

#### ACKNOWLEDGMENTS

Many individuals in the utility industry and many published papers have provided the source of the historic data and suggestions for improvement. The papers are listed in the accompanying bibliography, but the individuals are too numerous to mention here. One of the helpful sources was an illustrated booklet of seismic damage to electrical equipment, published A. J. Schiff of Purdue University.

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# JOURNAL OF THE TECHNICAL COUNCILS OF ASCE

## COMPUTER HARDWARE FOR CIVIL ENGINEERS

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(Reviewed by the Technical Council on Computer Practices)

### INTRODUCTION

Strictly, hardware is the circuitry of the computer and associated cabinetry, and does not include peripherals (e.g., terminals, and cardreaders) or internal representation of data. A civil engineer, however, generally views all that is not program as hardware. Therefore, this paper covers hardware and related topics.

There are three primary reasons for civil engineers to understand hardware:

1. The physical limitations of a computer are determined by its hardware. For example, word size sets the numerical accuracy of the machine and affects the handling of character strings. Often, knowledge of these limits is used to improve program efficiency.
2. The hardware determines the speed, capacity, and cost of a computer. This information is crucial when purchasing equipment.
3. Hardware governs the compatibility and communications between devices, such as terminals, remote sensors, and computer controlled machinery. Civil engineers need to be aware of interfacing requirements.

A complete analysis of hardware is neither possible nor warranted. Instead, fundamental concepts are introduced and appropriate references cited for further study.

### DIGITAL FUNDAMENTALS

**Binary System.**—All digital computers are based upon the binary system, a system with only two states—on/off (also referred to as yes/no, high/low, true/false, and 1/0). Information is stored, retrieved, and manipulated as a

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series of these simple states, where each simple state is called a "bit." Thus, all information is stored as a series of bits.

The binary system is best understood by examining the decimal system, our standard number system. In the decimal system, numbers are represented as combinations of multipliers and implied powers of 10. The binary system is similarly based upon combinations of multipliers and implied powers of *two*.

Other number systems exist. The octal system is based upon eight and the hexadecimal system based upon 16. [In the hexadecimal system, symbols *A*, *B*, *C*, *D*, *E*, and *F* are used to represent multiplier values of 10, 11, 12, 13, 14, and 15, respectively. Thus  $1B = (1 * 16^1) + (11 * 16^0)$ .] Powers are implied by the position of the digit with the right-most position implying a power of zero. Successive positions to the left imply successive powers of the given base. The digit is the multiplier, and for any given base, the largest required multiplier is one less than the base (e.g., the largest multiplier required in base 8 is 7).

Because conversion from hexadecimal and octal to binary is simple, and because representations in higher bases require fewer symbols to express a number, hexadecimal and octal are often used in hardware analyses.

The binary system has some special functions: NOT, AND, OR, XOR, NAND,

TABLE 1.—Logical Operations

<i>A</i> (1)	<i>B</i> (2)	NOT ( <i>A</i> ) (3)	( <i>A</i> ) OR ( <i>B</i> ) (4)	( <i>A</i> ) NOR ( <i>B</i> ) (5)	XOR (6)	AND (7)	NAND (8)	XAND (9)
0	0	1	0	1	0	0	1	1
1	0	0	1	0	1	0	1	0
0	1	1	1	0	1	0	1	0
1	1	0	1	0	0	1	0	1

and NOR. These are called logical functions because of their similarity to true/false patterns of logical inferences (5,9). With the exception of NOT, which requires only one operand or parameter, each operation requires two inputs and produces one output as do the arithmetic operations.

The operation of each logical operator is given in Table 1, which shows the input states *A*, *B*, and the resulting outputs.

The NOR and NAND operations are combinations of NOT with OR and AND respectively; XAND (exclusive AND) is a combination of NOT and XOR (exclusive OR). Thus, the basic logic functions are said to be: NOT, OR, XOR, and AND.

**Word Size.**—As mentioned before, all information is stored as a series of bits. To perform all operations one bit at a time is, generally, not desirable. Instead a larger elementary quantity, the computer *word*, is chosen which contains a number of bits. Although a few computers have a variable number of bits per word, most have a fixed number. The number of bits per word is called the word size. For example, a computer which has 16 bits per word is said to have a word size of 16 bits, or to be a 16 bit machine.

The largest integer a computer can store is determined by its word size. (While double precision and other multiword schemes extend the range, the

effectiveness of these techniques is still governed by the word size.) If  $n$  is the word size,  $(2^n - 1)$  is the largest integer that can be stored (2). Thus, for a 16-bit machine, the largest storable integer equals 65,535.

The maximum size of memory is also controlled by word size. Each word in memory has a number assigned to it, called an address, so that it, specifically, may be referred to. The largest address, which equals the size of memory, is equal to the largest storable integer. Thus, a 16-bit machine can only have 65,535 words of memory. Some computers use multiple word addressing for additional storage, but at an expense of considerable overhead.

The next sections demonstrate the effect of word size on numerical accuracy and character manipulation.

**Numerical Encoding.**—Previously, this paper considered the encoding of positive integers to binary. This section expands that notion to include negative numbers, floating point, binary coded decimal (BCD), and complement schemes. An understanding of these schemes is often required by civil engineers to interpret error messages, interface peripherals, and determine accuracy limitations on computations.

TABLE 2.—Negative Number Encodings

Number (1)	Sign-magnitude (2)	Excess 3 (3)
4	—	111
3	011	110
2	010	101
1	001	100
0	000	011
-0	100	—
-1	101	010
-2	110	001
-3	111	000

Representation of negative numbers can be accomplished in two primary ways (5,9): (1) Sign-magnitude; and (2) excess code. Sign-magnitude uses the left-most bit to indicate the sign (0 for positive numbers, 1 for negative) and the remaining bits for the magnitude. This scheme, however, suffers from a major problem, zero may be stored two ways: +0 and -0. The excess coding scheme eliminates such difficulty. The magnitude of the largest negative number to be stored (usually half of the largest storable number) is added to all values before storing. Table 2 shows the results of such a system for a 3-bit machine. Because the number added is three, the technique is labelled excess-3 coding. This procedure also extends the range of numbers by one.

Before proceeding to floating point numbers, one final integer representation must be considered. Two's complement arithmetic (5) is used in many computers because of its ability to detect overflow (adding two numbers to produce a number exceeding the largest storable integer) and underflow (subtracting two numbers or adding two negative numbers to produce a number less than the maximum negative storable number), while maintaining the proper sign. To convert a binary number to two's complement: (1) Change all bits, 1's become

0's and 0's become 1's; and (2) add one to the result. The left-most bit is a sign bit. In this system subtraction is eliminated, negative numbers are simply added and a negative value is developed by taking the two's complement of the positive number. The magnitude of a negative number (all negative numbers have a 1 in the left most bit) may be found by taking its two's complement. A carry into this sign bit with no carry out of the sign bit indicates *overflow*; carry out of the sign bit with no carry into the sign bit indicates *underflow*.

Floating point numbers (those with fractional parts) are best understood by comparison with the decimal system. A decimal fraction (e.g., 0.75) is simply a combination of multipliers and implied *negative* powers of 10 (e.g.,  $7 \cdot 10^{-1} + 5 \cdot 10^{-2}$ ). Similarly, a binary fraction (e.g., 0.11<sub>2</sub>) is a combination of multipliers and implied *negative* powers of two (e.g.,  $1 \cdot 2^{-1} + 1 \cdot 2^{-2}$ ). The period in the decimal system is called a decimal point, likewise it is called a binary

TABLE 3.—ASCII Character Codes

Bits 4321 (1)	Bits 765							
	000 (2)	001 (3)	010 (4)	011 (5)	100 (6)	101 (7)	110 (8)	111 (9)
0000	NUL	DLE	SP	0	@	P		p
0001	SOH	DC1	!	1	A	Q	a	q
0010	STX	DC2	"	2	B	R	b	r
0011	ETX	DC3	#	3	C	S	c	s
0100	EOT	DC4	\$	4	D	T	d	t
0101	ENQ	NAK	%	5	E	U	e	u
0110	ACK	SYN	&	6	F	V	f	v
0111	BEL	ETB	'	7	G	W	g	w
1000	BS	CAN	(	8	H	X	h	x
1001	HT	EM	)	9	I	Y	i	y
1010	LF	SUB	*	:	J	Z	j	z
1011	VT	ESC	+	;	K	[	k	{
1100	FF	FS	,	<	L	\	l	
1101	CR	GS	-	=	M	]	m	}
1110	SO	RS	.	>	N	^	n	~
1111	SL	US	/	?	O	_	o	DEL

point in the binary system. Thus, a computer word could be partitioned into a binary integer portion and a binary fraction portion.

A more efficient floating point representation can be developed using a mantissa-exponent scheme (2,5). Scientific notation is such a scheme (e.g.,  $-0.4516 \cdot 10^{-2}$ ). For the binary system, the mantissa is a signed binary fraction and the exponent a signed binary integer. Thus, 110.11<sub>2</sub> can be expressed as 0.11011<sub>2</sub>  $\cdot 2^3$ ; the process of moving the decimal or binary point is normalization. In practice, a word is divided into two segments, usually of different lengths. The number of bits in the mantissa governs the accuracy, and the number of bits in the exponent governs the range of numbers that floating point can handle.

The final type of numerical encoding significant to a civil engineer is binary coded decimal. Various forms exist (9), but the concept is the same: decimal numbers are converted directly to binary in groups of four bits. While some

machines operate in BCD, its use is more common in peripheral equipment. The procedure suffers from inherent inefficiency: four bits can store 16 different codes, of which only 10 are used, thus, six codes are wasted (e.g., 241 in binary requires seven bits, in BCD 241 requires 12 bits).

**Character Encoding.**—Alphabetic characters, numerals, punctuation, and other special symbols, e.g., \*, \$, and control characters may also be represented by a series of bits. (Control characters are special keys used to signal special events to the computer such as Carriage Return, Bell, End of Transmission, and Pause.) Only two major patterns are used: (1) Extended Binary Coded Decimal Interchange Code (EBCDIC), primarily used by IBM; and (2) American Standard Code for Information Interchange (ASCII), used by most other manufacturers. Where as the concepts are the same, only the ASCII code is explained herein. Table 3 provides the bit pattern for each symbol. Because each symbol's bit pattern has a numerical encoding, the numerical value is often said to be the numerical value of the character (e.g., a blank has the bit pattern equivalent to 32<sub>10</sub> and thus, is said to have a character value of 32).

The ASCII code uses 7 bits to represent a single character; the EBCDIC code employs 8 bits (not all combinations are used). Thus, a 16 bit/word machine can store two characters per word. A *byte* is the number of bits required to store one character, generally considered to be 8 bits, thus a 16 bit/word is a 2 byte/word. Because different machines have different word sizes, it is often useful to discuss memory size in bytes, a consistent unit of measure. Some machines even have special functions to perform byte manipulations as opposed to full word operations.

Character packing is the process of putting two or more characters into one word of storage. Left justified packing indicates the first character is packed as far left in the word as possible, and conversely right justified packing puts the first character as far right as possible. Character packing is of concern when character manipulation (e.g., sorting) is to be done.

There are several other important features of these systems. The character codes are arranged such that *A* has a lower value than *B*. Thus, sorting into alphabetical order is the same as sorting into numerical order. Upper and lower case letters vary by only one bit, thus translation between cases may be done by AND or OR operations (without any testing!). The low value characters are the control characters, therefore the numerals do not have values equal to their number. Note that NUL, which is a no operation code, is not the same as a blank, a printing character which produces a blank space.

#### BASIC MACHINE OPERATION

**Central Processing Unit.**—A digital computer is composed of four major modules. Fig. 1 shows the relationships between the four modules. The solid lines show the movement of data and the dashed lines the flow of control or command signals. The control unit, memory, and arithmetic unit comprise the central processing unit (CPU), while Input/Output (I/O) devices are called the peripherals. The wires connecting I/O with the CPU are called bus lines. (On some machines, the main memory is treated as a peripheral and, hence, is also connected to the bus.)

The arithmetic unit also performs the logical operations. However, some

operations (e.g., multiplication) are performed by the hardware on one machine, and by a program on another (i.e., multiplication is done by a program via repetitive addition). Hardware performed functions are faster, but increase the cost of the arithmetic unit. Some machines even do matrix operations in hardware.

The control unit, while the most important part of the computer, is usually of little concern to a civil engineer. It is important to realize that the control unit extracts its commands from memory. Thus, memory must be large enough to store *both* data and programs simultaneously.

**Memory.**—Memory is divided into two parts: (1) Primary storage, such as magnetic core; and (2) secondary storage, such as magnetic tape and disk. Secondary memory is usually viewed as one or more peripherals, however, it is often used as supplemental data storage for large programs.

Two forms of memory exist: (1) Read-write memory allows data to be stored and retrieved; and (2) read-only memory only allows the data to be read. The latter form is employed when commonly used programs or data (e.g., sine subroutines, or logarithm tables) should be indestructable.

While primary memory is random access (RAM), that is, any word of storage can be individually written or read, secondary memory may be either random access or sequential access, where words must be read, in order, until the

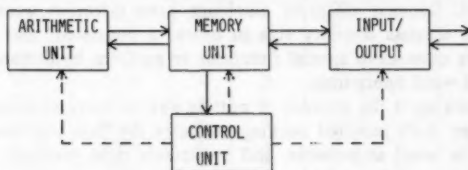


FIG. 1.—Elements of Computer

desired information is found. Magnetic tape storage is an example of sequential storage. (Magnetic disk storage is a blend of random and sequential access storage, but is considered to be random access.)

Various hardware configurations are used to implement primary memory (1,5,9). Core memory consists of small circular magnets, whose polarity can be sensed and controlled by the computer. Core memory has been the leader in primary storage until recently, when semiconductor memory costs have become competitive. Semiconductor memory, also called solid state memory, consists of transistor circuits which have two stable states (9). Semiconductor memory is faster and smaller than core. Other memory types, such as bubble memory (1), are being developed for further increases in speed while reducing cost and size.

Memory is measured in words of storage. (Storage is sometimes measured in bytes to avoid the ambiguity caused by word size.) Memory is so large, however, that a short form of notation has been developed. One K of storage is 1,024 words of storage; 1,024 is the smallest power of two larger than 1,000 (1,024 is also the largest storage integer for 10 bits, therefore 10 bits can address 1 K of storage). Thus, a 64 K word memory actually contains 65,535 words of storage.

A word of storage is the smallest directly accessible unit of storage on most computers. Thus, additional processing is required if only a portion of a word is considered. Some machines have special functions which can access storage by bytes; these machines are called byte addressable. However, the maximum size of storage then becomes  $n$  bytes instead of  $n$  words, in which  $n$  = the largest storable integer. Byte addressable machines are particularly useful in character manipulation environments.

Virtual memory is a scheme, implemented by hardware or software, or both, which appears to increase the memory of a computer. In essence, only those portions of the program and data that are being processed are kept in primary storage. Required and no longer needed information is swapped between primary and secondary storage. This swapping is transparent to the user. While this process extends memory to the size of secondary storage limits plus primary memory storage size, considerable overhead (i.e., processing time and I/O operations) is added to the computer.

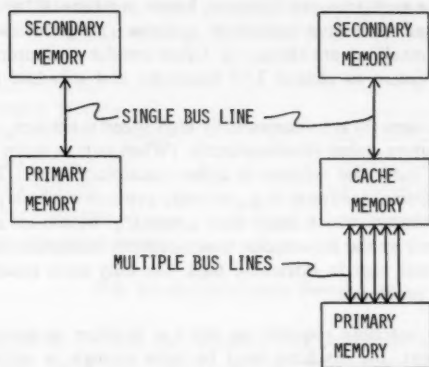


FIG. 2.—Standard Versus Cache Memory

Cache memory, often employed with virtual memory, is a hardware system to speed the swapping of information to and from primary and secondary storage. Under normal conditions, data is transferred one word at a time over a single bus line or "wire" (see Fig. 2). Cache memory transfers many words of storage into a temporary storage area (the cache) while the CPU is processing the information in primary storage. When swapping occurs, transfer occurs over multiple bus lines, thus reducing swapping time.

**Computer Size.**—The size of a computer does not refer to physical dimensions, but rather, is a measure of parameters such as word size, speed, memory capacity, and hardware functions. While exact boundaries are not defined, there are five classifications of computer size:

1. Microcomputers, or microprocessors are the smallest computers. (A computer must, among other things, be able to manipulate characters. Thus, a pocket

calculator does not qualify as a computer.) The CPU is contained in one or a few integrated circuits, called chips. Processing is slow, word size (and therefore memory capacity) is small, and hardware functions are usually limited. The cost is low, however, making them well suited to small specific tasks (e.g., text editing, simple computations), in fact many contain programs embedded in the circuitry. Home computers (1) are of this class.

2. Minicomputers are general purpose computers with medium speed capabilities. The CPU consist of many chips and memory capabilities of up to 64 K are common. Hardware functions usually far exceed those for microcomputers. Word sizes seldom surpass 16 bits and costs are significantly higher than microprocessors.

3. Small main-frame computers, or maximinicomputers, are minicomputers with special hardware features. The existence of virtual memory is considered to be a key feature. Hardware is implemented to operate at high speeds.

4. Large main-frame computers are high speed, general purpose machines. Memory capacities range from 64 K to beyond several megawords of storage. Virtual and cache memories are common. Large numbers of hardware functions are available, and extensive operating systems (programs which supervise operation of the machine) are employed. Often smaller computers are connected to a large main-frame to control I/O functions and schedule programs to be run.

5. Supercomputers (8) are exceptionally high speed machines, often consisting of several computers acting simultaneously. (When two or more CPU's simultaneously process data, the scheme is called multiprocessing.) These machines usually contain special hardware (e.g., an array processor which performs matrix operations in hardware) which limits their generality. Memories are always large and usually shared by the processors; many primary memories may exist within one machine. Their cost is extremely high, but only such machines can solve certain complex problems.

The size of a machine required to solve a problem is governed by many factors. Paramount, the machine must be large enough to solve the problem, but much leeway exists due to virtual memory, proper management of secondary storage, and space-efficient algorithms. [Accuracy (number of bits/word) and special required hardware operations, as well as primary memory capacity, may determine the required computer size. In addition, some problems require high speed to be solved within a reasonable time limit.] Economic factors then control. A large amount of time on a small machine or a small amount of time on a large machine may be used. Alternately, the availability of a particular computer may override other economic constraints.

#### PERIPHERALS

**Communications.**—A civil engineer need not be concerned with all the specifics of communication and interfacing (4,6), however, certain basic terminology should be understood. This basic knowledge is required when purchasing peripherals (e.g., terminals) and is useful in understanding some of their limitations.

While multitudes of peripherals exist, all peripheral devices must communicate with the CPU. In order to facilitate the interface of different peripherals, certain conventions are followed. Often conventions for different aspects of operation

can be employed simultaneously, however, use of one standard may preclude the use of another (i.e., some standards cover more than one aspect of operation).

Data is usually transmitted between the CPU and peripherals one word or byte at a time. This collection of bits may be transmitted using as many wires as there are bits (parallel transmission), or one bit after the other through one wire (serial transmission). While parallel transmission is faster, it is more costly due to the added wiring. It is not uncommon to use a blend of serial and parallel transmission.

The transfer of data must be synchronized between the CPU and peripheral to distinguish where one bit begins and another ends. An obvious technique is to have the CPU send a timing signal with the data. This is called synchronous transmission. This method, however, requires the peripheral to receive and process the data within the timing cycle. Modern computers operate at such high speeds that the length of cable becomes a controlling factor, in fact, limiting synchronous transmissions to distances of less than 15 ft. The alternative is to have the computer retain the signal until receiving an acknowledgement signal from the peripheral indicating it has processed the information. This alternative is called asynchronous transmission, and is not subject to any distance require-

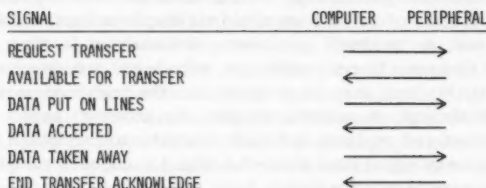


FIG. 3.—Asynchronous Dialogue

ments. The signalling between the computer and peripheral is usually expanded to provide a full dialog (see Fig. 3), and the interaction is often referred to as "handshaking." If the computer is the recipient, the direction of the data and acknowledgement signals are reversed. A third type of synchronization, the "20 mA current-loop" system, is sometimes used. It is, essentially, an asynchronous system, but with reduced voltage signals, and is used for short distance asynchronous transmission.

The rate of transfer between devices is measured in "baud," where 1 baud equals 1 bit/sec. During asynchronous transmission extra bits, beyond data bits, are transmitted. These extra bits are start bits, stop bits, and parity bits; usually one, two, and one respectively. Thus, if an ASCII character code, 7 bits, is to be transferred, then 11 bits must be transmitted. Thus, 110 baud is equivalent to 10 ASCII characters/sec.

The minimum number of wires for transmission is governed by the number of signals to be handled. If transmission is one directional, then only one wire is needed (ground is assumed to be established, and control lines are neglected). This one-direction operation is called simplex. If two-direction operation is required, but only one-way at a time, then the single wire may be shared. This is half-duplex operation. If simultaneous bidirectional operation is required,

then two wires are needed: one for sending, and one for receiving. This is full-duplex operation, and has an important use. When a key is pressed on a terminal, it is desirable to have the character print at the same time. In half-duplex, the signal from striking the key is split, with one part going to the computer and the other for local printing. This signal splitting is known as "echoplex," and is sometimes found as a switch marking on modems. There is no check, however, to guarantee the computer received what was typed. In full-duplex operation, the signal is sent to the computer which "echoes" it back to the printing portion of the terminal, thus providing a visual check on transmission. Some data should not be echoed (e.g., passwords), thus a method is generally provided to stop the echo; this is known as "echoplex suppression."

Occasionally, a terminal user or a peripheral (for various mechanical reasons, e.g., out of paper) requires the computer to temporarily suspend transmission. A special character is sent from the peripheral to the computer to stop transmission and another is sent to restart transmission. This scheme has many names depending upon the special characters sent; the most common name is XON/XOFF.

If data is to be transmitted over some distance, telephone lines become the obvious solution. Telephone lines do not transmit D.C. signals, thus, the information must be modulated, transmitted via telephone lines, and demodulated on the other end. A "modem" (*modulator/demodulator*) is, thus, required on each end, and they must be compatible (i.e., encode and decode exactly opposite to each other). Modems may be coupled into the telephone system directly via wiring, or through an acoustic coupler. An acoustic coupler cradles the telephone handset, and produces and receives audible tones through the handset. The fixed frequency signal onto which the data is encoded is called the carrier, and it must be present whether data is being transmitted or not.

As mentioned initially, specific interfacing techniques can be used simultaneously. This compination can be standardized itself. The Electronic Industries Association (EIA) has developed a standard interface (4) labelled the EIA RS-232-C interface. This is the most common type a civil engineer will encounter.

**Terminals.**—A computer terminal is the peripheral most frequently used by a civil engineer. All interactive processing (a mode of data processing where the user is in direct contact with the machine and can "converse" with the machine) is done through a terminal. In addition, engineers often prepare batch jobs (the opposite of interactive; where the user submits his/her data and has no control until execution is complete) on a computer terminal and then submit them from the terminal; this process is known as remote job entry. While the number of available terminal types prohibits enumeration, certain mechanical processes are common.

All terminals have a keyboard that is organized similar to a typewriter. Terminal keyboards have more keys than a regular typewriter as some keys denote special operations to the computer. The control-keys, formed by holding the control key and typing an alphabetic key (similar to operation of the "shift" key for capital letters), are one set of special operation keys. The exact meaning of the control keys is dependent upon the computer the terminal is attached to.

One type of display is a CRT (cathode-ray tube) that is similar to a television screen. Two styles of CRT's are available: alphanumeric displays, capable of displaying letters, numbers, and special/punctuation characters; and graphic

displays, capable of alpha-numeric operation and drawing pictures. The latter style (8,10) is more expensive and both come in two varieties: (1) Storage; and (2) refresh varieties. Storage screens cannot erase a portion of the screen (i.e., the entire display must be erased) or display moving objects. (It is possible by taking advantage of the intensity increase during the drawing process to display moving objects, but is not generally practical.) Refresh screens provide these capabilities by redrawing the entire screen at high rates of speed, usually 60 times/sec. This redrawing process, however, requires more computer resources.

Printing displays comprise most of the remaining displays. Many mechanisms are used to produce the printed output, often called hardcopy. The most conventional mechanism is to connect a typewriter mechanism to the computer. This mechanism is called impact printing, where a preformed inked letter is struck against paper, and has a large number of moving parts. The matrix mechanism attempts to reduce the number of parts by forming each letter with a series of dots. Standard characters are produced in a  $5 \times 7$  or  $9 \times 12$  dot matrix via a single printhead (a device containing a matrix of needle-like hammers) by energizing the appropriate dots. The needles strike the paper through an inked ribbon. Two variations of the matrix approach are commonly used. The first variation is to remove the ribbon, heat the needles (in actuality, the needle hammers are replaced with small heat producing electrical resistors), and strike heat sensitive paper (i.e., paper that changes color when heated). The second variation is to replace the needles with ink sprayers and spray the ink directly onto the paper, thus, this is called an ink-jet matrix mechanism. Another method for producing hardcopy is to assemble the image photographically, or photoelectronically and print with photochemicals or electrostatics similar to photocopying machines. The final major method is to draw the desired output with a pen; plotting devices fall into this category. Each method has advantages and disadvantages which must be weighed for each application, including factors such as speed, cost, maintenance, and resolution (the precision with which the character is formed). (Resolution, often measured in points/inch, is extremely significant in graphics. Poor resolution will cause sloped lines to be jagged and detail to be obscured.)

A complete examination of computer graphics (10) is not possible, however, a civil engineer should be aware of a key item: graphic output is either raster or vector style. Raster graphics is performed by turning on or off (printing or not printing) dots. Thus, it is useful for shading and irregularly shaped objects. Vector graphics consists of straight line segments (some displays have circular segments), and is useful if a large display (with respect to resolution) is used with a sparse drawing or many long straight lines. Conversion between styles is usually possible.

None of the aforementioned terminals contain any processing power, and are thus called "dumb" terminals. Reductions in the cost of computer circuitry have led to the introduction of small processors, often specialized (e.g., capable of text editing), into terminals. These terminals are called "smart" terminals (3) and are becoming common. Smart terminals reduce the load on the computer and provide quick response for simple tasks. Some smart terminals are actually microcomputers with special programs.

**Line Printers.**—By technical definition, line printers are output devices which

produce hardcopy and print an entire line with one mechanical operation. Civil engineers generally call any printing device without a keyboard, a line printer. By this latter definition, any of the printing mechanisms used in terminals may be encountered in a line printer. Two additional mechanisms may also be employed: drum printer, and chain (or train) printer.

The drum printer consist of a drum of characters with a full character set ringing the drum for each print position. (A print position is any location in a line of output where a character may be printed.) Each print position also has its own hammer for striking the type. The drum is kept rotating, and the hammer is activated when the appropriate letter is rotated into place.

The chain or train printer is similar except the drum is replaced by a continuous loop of characters, which move across the paper. When the desired letter reaches the proper print position, the hammer for that position is activated.

The number of characters per line and the speed of printing are the major parameters of a line printer. Eighty characters per line is used on most small printers, but 130 is the standard for line printers. Speed vary from 110 baud (or terminal speed) to 10,000 *lines*/min of 130 characters/line.

It is important to note that line printers often have limited character sets (e.g., upper case only). Speed ratings should only be compared for printers with similar character sets. Further, character sets may be mechanically changed on some printers, or even programmed on others, but many printers have only one character set (a character set is sometimes referred to as a font in text processing applications).

**Magnetic Tapes.**—Magnetic tapes are a compact and inexpensive method of storing data or programs, or both. Physically, the tape is similar to that used in home recording, but is different in consistency and size. Reels are available in lengths up to 2,400 ft in length. They are sequential access; the computer must read all information until it finds the desired data.

The format or manner of encoding a tape varies enormously. However, certain parameters are common to all: density, a measure of the number of bits of information per inch of tape; number of tracks, a measure of the number of individual bits stored across the tape; character set used, ASCII or EBCDIC; parity, the mode by which errors are detected; record size, a measure of the number characters per information group (e.g., 80 characters/input line); block size, a measure of the grouping of records; and labelled or unlabelled, indicating the presence or absence of special data beginning the tape. With the exception of the number of tracks, and density (some drives support multiple densities, however) most other parameters can be accommodated through software.

Tape densities are measured in bits per inch (BPI). Standard densities for seven track tape are 200 BPI, 556 BPI, and 800 BPI. Standard densities for nine track tapes are 800, 1,600, and 6,250. While some tape drives handle two or more densities, the user must always supply the proper density setting.

Magnetic tapes are either seven track or nine track, and the tracks are spread across the tape. Each track contains one bit and by reading all tracks across the tape an entire character is input. Seven track is the older style, and not used very often. For a nine track tape, eight tracks are used to store the character (thus, either EBCDIC or the ASCII code may be used), and the final track used to store a parity bit (see section on "Error Detection").

Three character sets (or bit pattern representations) are used on magnetic

tapes: (1) EBCDIC; (2) ASCII; and (3) BCD. EBCDIC, which uses 8 bits per character, and ASCII, which uses 7 bits per character, are suitable only for nine track tape. BCD, which uses only 6 bits per character but has an extremely limited character set, may be used on seven or nine track tapes. Most machines have software or hardware available to translate between the different character sets.

Parity is explained in the "Error Detection" section. Parity for seven track may be odd or even, and must be specified by the user. Nine track tapes are always odd parity.

Record size is an indication of the number of *bytes* (or characters) grouped together to form a piece of information. Records may be fixed or variable in size, but most machines perform more reliably with fixed record lengths.

Block size indicates how many records are grouped together, and is usually given in bytes. One record/block is recommended for transferring between machines.

The physical significance of record and block size is that an unrecorded gap is left on the tape between records, and a larger gap left between blocks. These gaps are sensed by the tape drive and are used to synchronize the tape with the computer. The more frequent the gap the easier synchronizing is, but the less information can be stored on the tape.

Labels are used to identify the information that follows on the tape and are system dependent (differ from machine to machine). A general rule to follow for deciding on labels for a tape is: label if storing information, no label if transporting information.

A mechanical interlock is provided on every computer tape to prevent accidental overwriting of information. A small plastic ring must be inserted before a tape may be written on, conversely, removal of the ring prevents writing. A simple rule to remember is: *no ring—no write*.

**Disks and Drums.**—Disks and drums are electromagnetic storage devices, similar to magnetic tapes. In addition, to sequential access, both disk and drum memory allows for direct access; that is, any particular piece of information can be read or written without having to pass other data. This direct access capability allows faster operation if random information is required.

A drum consists of a cylindrical surface of magnetic material which is rotated past a fixed bank of read/write heads. The maximum time required to access any piece of data is the time for one revolution of the drum.

Disks are circular platters of magnetic material which are spun about their center, similar to a phonograph record. The transfer mechanism may be either fixed head like the drum or movable head, where only one head is moved across the disk. Further, these disks may be stacked on a common spindle to form a disk pack and a read/write head provided for each platter.

Floppy disks are very thin flexible disks, housed in a protective wrapper. These type of disks are primarily used in small systems.

Disk and drum capacities vary widely. Floppy disks range from 75 K to 500 K bytes of storage, and generally represent the low end of storage capacities. Standard disk packs can provide as much as 675 megabytes (675,000,000 characters) of storage.

**Cardreader.**—A cardreader is an electromechanical device for reading punched paper cards. Civil engineers often use this type of device for bulk loading of

data and/or programs prepared off-line (without the aid of the computer). Punched cards are generally of the 3.5-in.  $\times$  7-in. (88.9-mm  $\times$  177.8-mm) size, but other sizes are occasionally used.

Some cardreaders are equipped with the ability to sense blacken marks on the card. This capability is called optical mark reading (OMR).

**Plotters.**—The number of plotting devices available is large, but two primary types exist: electrostatic plotters, and pen plotters.

Pen plotters are analog devices where either pen or paper motion or both are controlled by motors whose actions are derived from digital signals. High line quality is the primary advantage of such devices.

Electrostatic printers compose an image on an electrostatic grid and then transfer the image to paper. These devices therefore produce images which consist of dots. The density of dots, which is directly related to image quality, is called resolution. Some of these plotters produce densities of 500 dots/in.

**Graphic Input.**—Many hardware configurations exist for the input of graphical information (10). These devices are so prolific that it is impossible to catalog them here. It is sufficient to indicate that suitable devices for two-dimensional processing exist, but that three-dimensional input devices have yet to prove practical.

**Analog Processing.**—Obviously, many events and operations are not digital, but are gradually changing phenomenon (e.g., position of an object, volume of sound, resistance of a strain gage). These phenomenon are called analog, and have an infinite number of values. To be input to a digital computer, they must be converted to digital signals; this is the purpose of an analog-to-digital (A/D) converter (3,6,8). The process assigns fixed valued outputs to ranges of input values.

Often, the reverse process is required (e.g., to control a cutting tool) and a digital-to-analog (D/A) converter is used. The conversion procedures are not exact and some accuracy, and hence information, is lost.

## RELIABILITY

**Reliability Rules.**—There are two rules which are said to govern computer reliability:

Rule 1. Garbage in . . . Garbage out.

Rule 2. Computers do *not* make mistakes. If a mistake occurs see rule 1.

The first rule is an obvious statement that incorrect input will not produce the correct result. The second rule states that virtually all errors are a result of the program or data, or both, not the hardware.

**Crashing.**—Crashing is a general term used to indicate that the computer is no longer processing. There are two sources of crashing: (1) Hardware; and (2) software. A hardware crash is caused by one or more electrical components failing. A software crash is caused by the operating system (the program which supervises the operation of the machine) encountering a problem it is not programmed to handle, thus, it suspends operation awaiting human intervention. It is important to realize that neither crash produces incorrect results, rather it produces no results.

**Error Detection and Recovery.**—Most hardware failures result in a single bit

being transposed, i.e., a 1 become a 0 or a 0 becomes a 1. The probability of multiple bit transpositions increases exponentially.

Parity (1,2,4,5,6,8) is a procedure to detect a single bit transposition. For every word and every operation an extra bit of information is processed. The state (1 or 0) of the parity bit is determined by summing up the number of bits that are on. In an even parity machine, the parity bit is set such that the sum is even; in an odd parity machine, the parity bit is set so that the sum is odd. If after some operation or transmission, the sum (or parity) is not correct (appropriately even or odd), then a bit has been transposed. This procedure will not detect if an even number of bits have been transposed, but will detect if an odd number have been transposed. Further, the process will not detect which bit has been transposed.

If a parity error is detected, two alternatives can occur: (1) The machine may halt; or (2) the operation can be retried, halting the machine after a fixed number of tries. The latter procedure is one used in fault-tolerant computer design. (A fault-tolerant computer is one with special designs to keep it operating under abnormal circumstances such as electrical component failure. These machines are more expensive than conventional computers.) If duplicate circuits exist, the problem may be circumvented by routing the operation to the duplicate circuit, a technique also used in fault-tolerant machines.

Alternately, a more sophisticated parity scheme, such as Hamming codes (7) can be used which indicate which bit is wrong and correct it. However, these schemes require more parity bits as the word size increases, thus requiring more overhead and special (i.e., expensive) circuitry.

Another class of errors are hardware detectable programming errors (e.g., divide by zero). After every operation, the computer checks and stores in a special location in the CPU, called the processor status word, the occurrence of these errors. Upon detecting an error, several options are available. The machine could simply stop. The machine could branch to a special set of instructions (called trapping) and give diagnostics. The machine could give diagnostics, and continue. The machine could simply ignore the error. The latter two options should not occur as incorrect output (as a result of bad input) will result.

Any procedure which detects an error and tries to correct it, even if control is relinquished to the user, is called error recovery. Some mistakes cannot be recovered from (e.g., loss of key circuits, or data).

## CONCLUSIONS

This paper has presented an introduction to those aspects of computer hardware that are relevant to a civil engineer. References are cited for those who require more information in an area. Digital fundamentals, central processing units, and peripherals were reviewed. A synopsis of error detection and recovery was provided.

In summary, this paper should provide both the neophyte and expert with a concise reference on computer hardware.

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# JOURNAL OF THE TECHNICAL COUNCILS OF ASCE

## BUSINESS PLAN FOR THE ESTABLISHMENT OF NATIONAL INSTITUTE FOR COMPUTERS IN ENGINEERING (NICE)

By the Computer Practices Committee of the Technical Council  
on Computer Practices

### PREFACE

This report proposes a business plan for the establishment of a National Institute for Computers in Engineering (NICE). It also identifies potential sources of funding for the NICE project. The document represents the work and effort of members of the Technical Council on Computer Practices committee (TCCP) in conjunction with members of the Society for Computer Applications in Engineering, Planning and Architecture (CEPA). This report is the result of a charge from the TCCP Executive Committee to the Computer Practices Committee to, "develop an implementation plan for the concepts contained in the NICE report approved by ASCE Board of Direction at its July 1978 meeting." This report was presented to and accepted by the TCCP Executive Committee at its October 1980 meeting. At that meeting the Executive Committee recommended that it be published as a Committee Report in the *Journal of the Technical Councils of ASCE*.

The business plan was prepared by an ad hoc committee appointed by the Computer Practices Committee and included the following members:

Barry B. Flachsbart  
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Hugh McGrory  
Glenn S. Orenstein  
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The portion of the report identifying potential sources of funding for the NICE project was prepared by an ad hoc committee appointed by the Computer

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Practices Committee and included the following members:

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This report is respectfully submitted by the Computer Practices Committee of the Technical Council on Computer Practices.

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#### SUMMARY

This document describes a proposed business venture, a National Institute for Computers in Engineering (NICE). NICE will be an independent, not-for-profit organization comprising engineering-related professional societies. Its prime purpose will be to provide an information service which will assist in promoting the effective use of computers and computer software as tools of the practicing engineer.

NICE will provide services for a fee to the practicing engineer. The principal service will be the provision of information on computer software based on systematic methods of information collection, computerized storage, and retrieval. This information will be classified and described so as to permit the prospective user to make intelligent selection and then to contact the owner of the software.

NICE will also provide a service to suppliers of software. This will consist of user feedback information which will permit suppliers to enhance existing products and produce new ones based on market demands.

The NICE concept has the approval and support of the American Society of Civil Engineers (ASCE) and other prestigious engineering organizations such as the American Consulting Engineers Council (ACEC) and the Associated General Contractors (AGC). It is directed towards improving the productivity of the engineering profession, and in turn, the national productivity. The importance of improved computer use by the engineering profession is underlined by the recent address by the Comptroller General of the United States, Elmer B. Staats (3) who said:

By more fully using computers, civil engineers could greatly improve the well-being of their companies, help our Nation solve some of its more pressing problems in energy, and reverse the productivity slump of our Nation's workers.

This business plan is designed to guide the creation and operation of NICE so that it may be a self-sustaining entity within two years.

## BACKGROUND

To find the genesis of NICE it is necessary to go back to the late fifties and early sixties. At that time, the computer was beginning to show, to the knowledgeable observer at least, the early signs of its awesome potential. A small number of engineers in various disciplines, i.e., government, private practice, universities, and industry and commerce, began to use the computer as a tool. It was not easy. During this period the world of computers was rather like the early days of the railroads in Europe in the nineteenth century. In the beginning there were very few suppliers, but with the North American entrepreneurial instinct they soon began to increase. Various types of hardware appeared, all different, just as the roadbeds of the early railroads used different gages; and, of course, like the rolling stock of those days, computer software was not generally interchangeable.

These difficulties were compounded by the fact that there was very little application software available. Everyone was still learning how to use the machines—there were few experts. It is not surprising then that only a small number of the engineering profession got involved.

It quickly became apparent to those engineers that while hardware and operating software were important, it was user-oriented application software that was the key to effective use. It also became obvious very soon that no one individual or organization could supply the amount and quality of software that the market would demand. So, as this growing but still very small segment of the profession began to develop application software, early cooperative efforts began to appear.

Of these cooperative efforts, the following are of interest.

### ASCE

The American Society of Civil Engineers was founded in 1852 and has more than 70,000 members. The objective of the society is stated as "... the advancement of the science and profession of engineering to enhance the welfare of mankind."

ASCE's early interest in computer applications was recognized when the Structural Division established a Committee on Electronic Computation in 1957. In 1973 a Technical Council on Computer Practices was created, to:

... establish the means by which the civil engineering profession will be able to properly utilize the impact of the electronic computer and its related software in civil engineering practice, research and education.

### CEPA

CEPA is an acronym for Society for Computer Applications in Engineering, Planning and Architecture, Inc. This organization was formed in 1965 in New York City. The purpose was to organize a not-for-profit computer program exchange group among civil engineering firms who were users of a specific computer, the IBM 1130. The meeting was attended by 22 engineers representing 19 civil engineering firms throughout the United States.

Today CEPA membership firms number more than 200, representing more than 25,000 professional staff all over the United States and Canada, and in such countries as Australia, England, France, Iceland, Malaysia, and Switzerland. More than 50 different computers are employed by these firms, and the applications cover the gamut of civil engineering activities.

### **ICES Users Group, Inc.**

ICES stands for Integrated Civil Engineering Systems. This is a system of computer programs originally conceived at the Massachusetts Institute of Technology for solving problems in structural engineering, highway design, geotechnical engineering, project management, surveying, and other branches of civil engineering.

The ICES Users Group, Inc. (IUG) was originally established in 1967 and is a cooperative organization sustained by dues and program reproduction fees to promote the dissemination of information on the ICES Executive System and on ICES application subsystems.

The IUG is an international organization with 525 member organizations in 30 countries. Three sections exist. One is primarily composed of members in the United States and Canada, one comprises primarily European members, and the third is comprised of organizations in Japan. Successful though these organizations were in their chosen areas of operation, it became apparent to many that wider needs still existed.

In 1970, certain members of the ASCE approached the National Science Foundation (NSF) for support for a special workshop on engineering software coordination. The NSF is, of course, the United States Government body whose mission is to initiate and support scientific research and programs to strengthen scientific research potential. The timing was good. The NSF was becoming aware of the fact that much of the money which they placed to support research was used to produce computer programs as tools of that research. However, most of these programs never saw use outside of the particular research project for which they were written. It was felt that some of this software would have more general application, and that a considerable resource existed that was not being used effectively. Support was granted, and in October 1971 a Special Workshop on Engineering Software Coordination was held at the University of Colorado at Boulder.

The objective of the workshop was the development of specific recommendations for the establishment of a policy concerning the transfer and utilization of computer based technology specifically applicable to civil engineering and building construction, and more generally applicable to the practice of engineering. The participants at this workshop, 46 professionals with extensive experience in computer use, recommended "... a National effort to optimize common use of engineering software . . ." and, "... the immediate establishment of a demonstration pilot program. . . ." The workshop recommended further that the organization and operation of the pilot program should be developed by the engineering profession as a whole.

The Steering Committee of this conference asked CEPA to assume the task of defining the form which a national effort should take. CEPA accepted this challenge, and in August 1972 presented a proposal to the National Science Foundation for support for a study entitled, "Definition of a National Effort

to Promote Effective Application of Computer Software in the Practice of Civil Engineering and Building Construction." This proposal was accepted by the National Science Foundation and CEPA was granted \$211,400 in late June 1973 towards the estimated cost of \$330,000. The study results were presented as a booklet entitled "A Proposal for a National Institute for Computers in Engineering," often referred to as the "NICE Report."

The NICE study recommended a series of activities which might be performed by a national center to help the profession to use computer software effectively. The foremost recommendation was that the center serve "... as a clearing house or broker for information as to available software, searching out and receiving such information from all relevant sources."

The principal problem remaining was that no mechanism could be found for implementation. Through the continuing efforts of the TCCP, the 1977 ASCE annual report provided a breakthrough in that it included, as an objective of the ASCE, the establishment of a National Institute for Computers in Engineering. The task of bringing this project to fruition was assigned to TCCP. A policy report on implementation prepared by this body was adopted and authorized by the ASCE Board of Direction at the October 1978 ASCE Convention, and was referred back to TCCP for action.

The Computer Practices Committee of TCCP developed an implementation plan, and at a meeting in Baltimore, Md. in June 1980 it set up an ad hoc committee to develop this Business Plan for NICE, Inc.

#### **BUSINESS PURPOSE AND OBJECTIVES**

The prime purpose of NICE will be to provide an information service which will assist in promoting the effective use of computers and computer software as tools of the practicing engineer.

The objectives of NICE, in order to fulfill this purpose, can be summarized as:

1. Making information about computer software and sources of software available to the practicing engineer, in order to encourage wider use of computers, to reduce duplication of effort spent on creating computer software, and thus to improve the productivity of engineers.

2. Implementing a mechanism for providing to software designers information obtained from formal solicitation of feedback from users regarding quality and availability of software. This will help to improve the quality and value of software and to broaden the software market.

These objectives will address many of the areas identified in the CEPA NICE Report as being the greatest inhibitors to effective computer use:

1. Limited design of software, making it too customized for general utility.
2. Distribution problems due to lack of information.
3. Lack of user experience feedback.
4. Lack of modification and improvement of software products.
5. Lack of post-degree educational opportunities.

An overall objective in fulfilling the purpose of NICE is to be self supporting. It is felt that fees generated from services will enable the endeavor to become self supporting after two years of operation, based on the following market analysis.

Once NICE is firmly established, it may be desirable to expand the scope of information available. NICE may, for instance, provide a service listing educational opportunities in the area of engineering computer use.

#### MARKET AND MARKETING PRIORITIES

**Services Offered.**—Two distinct information services will be offered: (1) Information on software availability for the practicing engineer; and (2) information on additional needs for the suppliers of application software. The initial overall aim and primary benefit of the service is to provide a means whereby an engineer can easily find existing application software which will meet his specific requirements. The secondary goal is to help the software developer to determine areas where additional capabilities may be required or where new needs are being generated—this will assist in the development of totally new application software or enhancements to existing packages. In both cases, the product is information.

At a later time, it may be desirable for NICE to expand its information base to include information relative to learning opportunities about computers and software available to engineers. This information might include lists of conferences and classes/seminars scheduled on various computer software related topics.

**Target Markets.**—The targets of this sale of information, then, are: (1) The practicing engineer and his associates; and (2) the supplier of application software or computer services. The practicing engineer who will make use of NICE will be an individual addressing a particular problem or need for which there is a possible (but unidentified) computer solution. This is the person who has the most to gain from using this service. He is the person to whom the service will be primarily directed. The major benefit to him is a savings of manpower and time that might otherwise be used in developing a unique solution where one already exists, or in searching through a variety of places where software may exist.

An easy and flexible means of formulating the search criteria must be provided. This capability will not only set a standard for the way in which criteria may be established and entered, but, most importantly, it will set a standard in the level, content, and type of documentation that will be received in response to an inquiry. This will assist in evaluation of the software's capabilities to fulfill the engineer's requirements in making a correct and timely selection, and in easily obtaining the software. It will also assist in the establishment of the credibility of the service itself.

Once the standards are established, the user will be encouraged to submit his critique concerning benefits, use, and problems of the software. This will increase the level of information which can subsequently be provided. The selection process will be enhanced by the indication of how various application software stacks up against other packages—not only from a functional standpoint, but, more importantly, from the actual user's standpoint.

The second target for our marketing activities, i.e., the supplier of application software, will also obtain many benefits from the use of NICE over and above the development of new opportunities for the sale or increased use of his software. By having access to the NICE data base, the supplier will have immediate access to information concerning the competitive situation in regard to his specific product. This will provide him with facts to help decide how or whether to correct deficiencies, or both, and to add additional capabilities or to develop totally new capabilities. The ultimate beneficiary of this increased feedback to the software supplier is, again, the practicing engineer who would then be likely to obtain better and more advanced capabilities to choose from to meet his particular requirements. The overall benefit to the entire profession will be the more effective use of manpower and, thus, improved productivity referred to in the Staats address (3). This will be achieved by reducing the need to develop unique but duplicate solutions where ones already exist, and by allowing the use of the skilled software developmental manpower which exists to develop application software to meet present and future requirements.

**Marketing Priorities.**—The success of NICE depends on building up rapid use of the capabilities of the information bank. In order for this to occur, the primary need is for the information bank to be as complete as possible and thus of maximum usefulness to potential inquirers. The number one priority then must be to ensure that the information is complete. Methods of accomplishing this depend heavily on support from organizations that have known large banks of software. These organizations must submit the software abstracts and encourage the use of NICE in order for it to succeed. In addition to such organizations, all of the known owners of engineering software, including service bureaus, equipment vendors, and software vendors, will be contacted. These vendors must be encouraged as strongly as possible to provide information about their software. One of the early tasks of NICE should be to create a list of both organizations and suppliers, along with contacts within each, in order to facilitate progress in obtaining a complete data base. Personnel from NICE may have to actively search out software which should be listed and even go so far as to fill out the listing information for entry, based on personal contacts with various suppliers.

The number two priority will be to ensure that access to the information bank is easy and flexible. Potential users must be able to access the information via low-cost time sharing, mail inquiry, or interface to their own computer system. Some of the access will also be via telephone contact to NICE personnel. A continuing study on access methods might be appropriate.

The number three priority will be to publicize the availability of the NICE information bank. Even with a complete bank, NICE will fail if potential users are not told about the bank and how to access it. Again, the various organizations will be key to this effort in that they can include articles about NICE in their newsletters and even include NICE brochures in mailings to their members. In addition, participation and demonstrations at major engineering conventions and trade shows will be necessary, as will exhibits at various specialty conferences and exhibitions. Obviously, articles in engineering news magazines and in other related publications will be used. Those individuals who have experience in publicizing specialty conferences will be most helpful in these efforts.

The fourth priority must be to establish pricing which is at the same time

fair, inexpensive, and sufficient to support the service. For the purpose of launching the NICE project, an initial price structure has been established (see the section on sales plan and forecast). This will have to be reviewed and modified in response to actual market needs.

A final priority will be to ensure ways of keeping the information bank up to date. As the NICE concept succeeds, the natural outcome will be to have ever-increasing amounts of software abstracts and critiques submitted. Thus, NICE must be prepared to cope with rapid expansion of the information bank as well as with large numbers of critiques.

In summary, there appears to be five priorities which must be pursued for NICE to succeed:

1. Ensure that the information bank is complete.
2. Ensure easy and flexible access to the information.
3. Publicize the availability of the NICE information.
4. Establish pricing with great care.
5. Provide for keeping information up to date.

**Potential Problems which May Impede Marketing.**—The attractiveness of submitting information to the NICE bank is proportional to amount of difficulty (time, generally) in preparing the information for submission. One possible problem may be in getting potential software suppliers to revise their product information to the format that NICE will require. One way to meet this problem is to require only the minimum of information to provide a meaningful answer to an inquiry and make all other portions of the requested information optional. Then, as the suppliers begin to see the advantage of putting information into NICE, they will gradually improve the quality and quantity of the information available on their products.

Another potential problem, closely related to the first, is the ease of updating information. This applies to potential critiques as well as to product information. Any lengthy review process will cause severe difficulties with the accuracy of the information and the ability to maintain current data. Reviews of information must be rapid. Of course, there must be no cost to the user for generating a critique.

The search mechanisms must be extremely user friendly as well as swift. This is another potential problem. The user interface must be specifically designed for the user, not for the programmer. A well-written user manual will be invaluable in this regard.

One final problem may have to be addressed. Prices for access to the information bank may be fixed, i.e., so much per inquiry, or based on the amount of computer effort it takes to carry the request out, i.e., usage charges, like a time-sharing service. In any event, the actual costs of access to the data base are changing at all times. As the number of entries increases, the costs to access an entry are different. As the amount of information in an entry increases (more of the optional information is given or more user critiques are received) the costs of providing that information increases. With the pricing set at a fixed charge, the supplier of the data base processing may be financially hurt; with the usage charging method, the costs to the user cannot be estimated and will certainly increase as the data base improves. This potential problem must be considered

in the final deliberations about pricing and the search mechanism, which must provide flexibility in criteria, but yet provide some limit on the extent of any particular search. Initially, it is proposed that the fixed-charge scheme be employed.

## SALES PLAN AND FORECAST

### Phase I: Introduction to Engineering Community

**Objectives.**—The objective of the first phase of the sales program is to introduce NICE to the engineering community and to promote an understanding of its purpose, capabilities, and how it may be promoted. In particular, the first phase will provide recognition of NICE to potential suppliers of software listings in order to rapidly increase the NICE data base.

**Target Audience.**—The first target of the Phase I sales plan is the body of practicing engineers. Specific attention will also be paid to the officers and governing boards of the various engineering societies and professional organizations. The latter target is to be emphasized because it is essential to encourage the active participation in NICE of all engineering affiliations. Additionally, the leaders of these societies, by the nature of their position, experience, and temperament, are looked upon as primary sources of information by the engineering community at large. These people can be depended upon to spread knowledge of NICE activities by means of personal contact.

The other target sector of the Phase I sales plan consists of the sources of engineering software to be listed with NICE. Before NICE can begin to offer any meaningful service, extensive work must be done in assembling an initial data base for information retrieval. This will require the submission of a large number of program abstracts. Phase I will provide the "marketing" necessary to get the cooperation of software providers. This sector will include the following potential sources: (1) Engineering firms having computer software which they are willing to distribute; (2) "software houses"—companies whose business is the creation of engineering computer programs; and (3) computer service bureaus and timesharing organizations—those in the business of marketing computer time and software services.

**Activities.**—The following sales oriented activities will be pursued as part of Phase I:

1. **Journal articles.**—Articles will be written and placed in the "popular" engineering journals such as *Civil Engineering* of the ASCE, the *CEPA Newsletter*, or *Mechanical Engineer* of the American Society of Mechanical Engineers (ASME). These articles will be short (many times only a paragraph or two), and will be frequent.

2. **Exhibits at engineering society meetings.**—A portable exhibit will be created and displayed at engineering society meetings in order to catch the attention of attendees. Literature describing the purposes and capabilities of NICE will be available at the display. A single person will be all that will be necessary to set up and staff the exhibit.

3. **NICE newsletter.**—A newsletter will be issued to all interested parties. Included in the newsletter will be advertisements in order to produce enough

revenue to cover the cost of publication. Potential advertisers are service bureaus and software houses.

4. **Direct mail.**—Direct mailings will be issued to the mailing lists of the engineering societies. Attention will be paid to selecting from those mailing lists names which would have a high potential of interest in NICE. All of the CEPA lists or those of the group Automated Procedures for Engineering Consultants (APEC) would be used, while ASCE or ASME might be limited to those members who have indicated special interest in computers.

**Timing.**—The initial sales phase will last from 6 months–9 months. There will not be an abrupt change into the next phase. The transition will be gradual, and will begin at such time as an adequate staff and data base are in place to enable work on Phase II.

**Expected Return.**—Inasmuch as the objective of Phase I is not sales but recognition, it is expected that there will be no revenue generated during this startup period. The operation of NICE during Phase I will be entirely supported by grants and contributions.

## **Phase II: Operations Phase**

**Objectives.**—The needs and activities of Phase I will never really end. There will always be a need to introduce NICE to new members of the engineering community. Nevertheless, as NICE develops the necessary data base and the required staff, the sales activities will change over from an introductory phase to a more mature steady-state phase. The objective of the Phase II sales program is to make the routine and frequent use of NICE an accepted form of engineering practice.

**Target Audience.**—The sales activities of Phase II will concentrate on those members of the engineering community who have specific though possibly tangential interest in computer use. The target audience will consist of: (1) Experienced users of computers who have a need to rapidly search for potential software aids; and (2) novice or noncomputer users, who have recognized the potential benefits of computers and seek an authoritative source of information and source of instruction on computer software availability.

**Activities.**—In addition to a continuation of and a broadening of Phase I activities, certain new activities will be added to the sales effort:

1. A brochure will be developed to list the categories for which the data base may be searched, and to give brief examples of the types of searches which may be conducted.

2. A comprehensive "examples" brochure will be developed giving a step by step description of the search procedure.

3. A rate card listing categories of service will be printed and distributed by direct mail to a general mailing.

4. A demonstration package will be developed to be used at conferences, local society meetings, or engineer's offices. This package will consist of several sample inquiries and the results obtained.

**Timing.**—Phase II can begin as soon as there are a sufficient number of entries in the NICE data base to make use of the service attractive to engineers.

This will occur approximately 6 months–9 months after the start of Phase I.

**Fee Structure.**—Every search which is conducted will incur a service bureau expense. These expenses will be passed through to the NICE subscriber. NICE will derive its revenue by means of a surcharge or fee to be paid by the subscriber over and above the passed-through service bureau charges.

The fee structure is based upon the type of search conducted and the manner in which that search is initiated. The request for a data base search may be made by the user from his own timesharing computer terminal. In this case, the involvement of NICE staff is minimal. A request may also be initiated by telephone conversation or letter to NICE. In this case, staff involvement will be greater.

There are two types of searches. Keyword searches will be conducted to find all computer programs meeting a list of given requirements (keywords). Feedback searches will provide a report of all user feedback for one specific computer program. Because of the direct nature of a feedback search, less effort and fewer computer resources are required than for a keyword search.

The following fee structure is anticipated:

**NICE Data Base Search Fee Structure (in Addition to Service Bureau Expenses)**

Search Type:	Keyword Search	Feedback Search
How done		
Letter or telephone request:	\$25	\$25
User's own computer terminal:	\$20	\$15

**Expected Return.**—During Phase II, actual sales of services by NICE will mature. The following sales are projected from an estimate of 16,000 engineering firms, construction companies, and related manufacturing organizations. Initial projections for sales are based upon the following analysis:

1. There are approximately 11,000 civil engineering consulting firms in the United States (2) and another 2,000 are estimated to be in Canada. In addition, there are 2,000 major construction firms as well as an additional 10,000 other possible NICE users comprising universities, government departments, other engineering consultants, industrial organizations, and other nonengineering organizations in the two countries. The total is approximately 25,000 possible user organizations.

2. It is assumed that the use of NICE will grow until, in any one year, 20% of the possible users will actually make use of NICE. This is 5,000 actual users.

3. It is also assumed that the average firm making use of NICE will do so five times in one year. This is a total annual request load of 25,000 requests/yr, or approximately 2,100/month.

4. Because most of the requests will come directly from the users' terminals, the average charge per request will result in revenue of \$20, which will yield an income of \$42,000/month, or \$504,000/yr.

5. The number of requests per month will build from a value of 0/month in the twelfth month of NICE operation to the ultimate of 2,100/month some 21 months later. This will result in the following annual revenue:

Year of Operation	Expected Number of Inquiries	Expected Revenue From Inquiries
1	0	\$0
2	7,800	\$156,000
3	21,600	\$432,000
4	25,200	\$504,000
Subsequent years	25,200	\$504,000

#### ORGANIZATION AND ORGANIZATIONAL STRUCTURE

NICE will be controlled by a Board of Directors initially composed of two persons appointed by ASCE, two persons appointed by CEPA, and one person

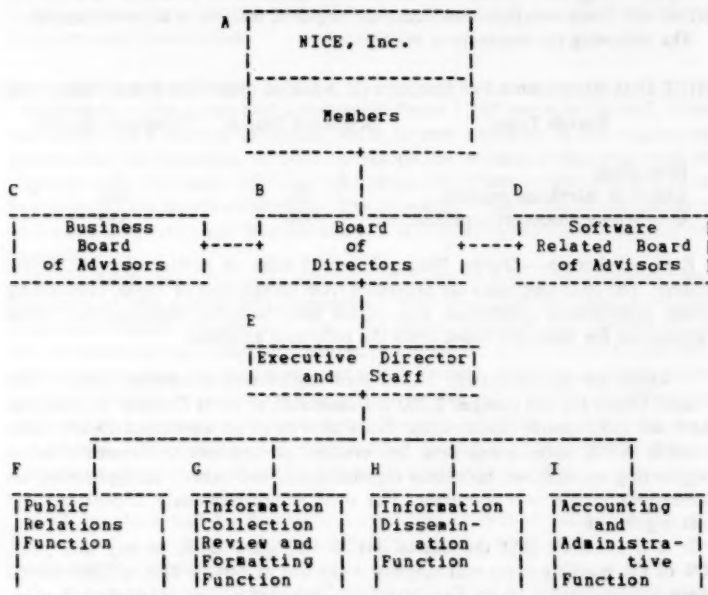


FIG. 1.—Organization of NICE

appointed by IUG. ASCE, CEPA, and IUG would be deemed to be members of NICE. Mechanisms for expanding the number of members and the Board of Directors will be specified in the bylaws.

The proposed organization structure is reflected in Fig. 1. The following describes some of the key elements in that organization.

**NICE and Its Members.**—NICE will be organized as a not-for-profit corporation.

Membership in NICE will be extended to engineering-related professional societies. The member societies will be represented by a society appointed or elected representative who will act as liaison to NICE.

**Board of Directors ("B" on Fig. 1).**—A Board of Directors will comprise a selected number of the society representatives. Initially, the composition of the Board of Directors will be as previously established.

The Board of Directors will be the legal governing body of NICE. Its first order of business will be to write the operating bylaws of NICE and to have them accepted and ratified by the member societies. Subsequently, composition of the Board of Directors will be dictated by the bylaws.

**Business Board of Advisors ("C" on Fig. 1).**—This board will advise the Board of Directors on the business decision aspects of NICE. They will provide guidance on the feasibility and cost of providing or not providing services. Board members will be selected from members and commercial organizations who are active in and supportive of NICE.

**Software Related Board of Advisors ("D" on Fig. 1).**—This board will advise the Board of Directors on the software related decisions relative to NICE. They will assist in developing standards of information collection, retrieval, and dissemination. Board members will be selected from user groups, professional societies, and commercial organizations who are active in the use and support of computer applications.

**Executive Director and Staff ("E" on Fig. 1).**—As all of the previous groups are mainly policy makers and advisors, the Executive Director and Staff will be the action arm of NICE. The Executive Director and attendant staff will direct the day-to-day NICE activities to execute the Board's wishes. It is possible that some economy may be realized by sharing staff functions with other related organizations.

The functions of the Executive Director and Staff are shown on Fig. 1 in boxes F through I. The functions are: (1) Public relations; (2) information collection, review, and formatting; (3) information dissemination; and (4) accounting and administrative.

#### IMPLEMENTATION PLAN

The implementation plan will be accomplished by completing the following 10 steps:

1. Member approval.—ASCE, CEPA, and IUG members must formally agree to be members of NICE and appoint representatives to the Board of Directors (as of this writing, ASCE, CEPA, and IUG have agreed to join and support NICE. As such, two ASCE members, two CEPA members, and one IUG member for the Board of Directors have been designated).

2. Initial financing.—Initial financing must be addressed immediately. As such, an Ad Hoc Committee has been appointed by ASCE and CEPA to investigate sources of funding. The report of the Ad Hoc Committee is attached to this business plan as Appendix II.

3. Incorporation.—Incorporation requires legal and financial advice which might be borrowed from the ASCE, CEPA, or IUG. Other corporate adjuncts, such as articles of incorporation, bylaws, and corporate seal will be required.

4. Appoint advisory boards.—The Board of Directors in conjunction with member organizations and other organizations must solicit candidates for these advisory boards. The NICE Board of Directors will determine final members for these advisory boards.

5. Resources.—The initial staff will comprise five individuals: (1) The Executive Director; (2) the Information Administrator; (3) a Technical Assistant; (4) a Secretary-Bookkeeper; and (5) a Secretary-Receptionist. Initial office space and facilities must be obtained along with adjunct resources such as computer accessories, terminal, telephone facilities, etc. It is recommended that, if possible, some of the support functions and office space be acquired from member organizations.

6. Establish details of information collection, storage, retrieval, and dissemination.—Define format and content for collection of information, storage, retrieval, and dissemination of the information base. Must design or select a system to provide for the storage of the information in a computerized data base. The details of retrieval and dissemination must also be designed.

7. Finalize pricing method.—The Executive Director, with approval from the Board of Directors, must develop a pricing method that will insure that NICE is self sufficient within 2 yr.

8. Information, collection, and storage.—As many organizations as possible must be contacted for information about software in their libraries. Specific organizations include CEPA, APEC, National Information Service Earthquake Engineering (NISEE), Control Data Corporation (CDC), McDonnell Douglas Automation (McAUTO), United Computer Systems (UCS), University Computing Company (UCC), The University of Colorado Highway Engineering Exchange Program (HEEP), The University Software Exchange Program Hydrologic Engineering Center of the Corps of Engineers (HEC), and other service bureaus, computer manufacturers, and software houses.

9. Publicity.—Publicizing of NICE in accordance with the marketing and sales plan must be carried out. This publicity will be directed primarily at end users.

It is anticipated that the implementation activities such as appointing boards, financing, and collecting information will generate early publicity giving prestige to NICE.

10. Begin operations.—At start-up time, the staff should direct their priorities, when not handling information requests, to soliciting additional information for known deficiencies in the data base and requesting feedback information from users.

#### **APPENDIX I.—BUDGET AND CASH-FLOW REQUIREMENTS**

On the following pages are the anticipated budgetary requirements for the first two-year period of NICE existence. Also included is a cash-flow breakdown for the same period. The proposed budget represents the most modest estimate which would enable operation and delivery of services.

Appendix II of this business plan represents the report of the ASCE Ad Hoc Committee for Identifying Sources of Funds. The suggestions of the Ad Hoc Committee will form the basis for obtaining the necessary funds to support the budget requirements as listed.

## First Year Budget

## First Year Expense

1. Salaries:		207,500
Executive Director	60,000	
Information Administrator	35,000	
Technical Assistant	25,000	
Secretary—Bookkeeper	16,500	
Secretary—Receptionist	13,500	
Bonuses	20,000	
Fringes	37,500	
2. Office rent		18,000
3. Office supplies		10,000
4. Postage		20,000
5. Telephone		36,000
6. Travel		25,000
7. Printing		15,000
8. Promotion		15,000
9. Furniture and equipment		13,000
10. Outside accounting, legal, and other services		15,000
11. Contract data base acquisition		200,000
12. Contract data entry—data base		10,000
13. Contract funding assistance		100,000
14. Miscellaneous		20,000
Total:		\$704,500

## First Year Revenue

1. No inquiries	0
2. Outside grants	725,000
Total:	\$725,000

## Second Year Budget

## Second Year Expense

1. Salaries:		228,400
Executive Director	66,000	
Information Administrator	38,500	
Technical Assistant	27,500	
Secretary—Bookkeeper	18,200	
Secretary—Receptionist	14,900	
Bonuses	22,000	
Fringes	41,300	
2. Office rent		19,800
3. Office supplies		11,000
4. Postage		22,000
5. Telephone		40,000
6. Travel		45,000
7. Printing		16,500
8. Promotion		16,500

9. Furniture and equipment	2,500
10. Outside accounting, legal, and other services	16,500
11. Miscellaneous	23,000
Total:	\$441,200

## Second Year Revenue

1. 7800 inquiries	156,000
2. Outside grants	275,000
Total:	\$436,000

## Cash Flow by Quarter: First Year

	First Quarter	Second Quarter	Third Quarter	Fourth Quarter	First Year
Cash on Hand	—	1,875	8,750	37,125	—
Income:					
Inquiries	—	—	—	—	—
Grants	100,000	150,000	200,000	275,000	725,000
Expense:					
Salary & fringe	46,875	46,875	46,875	66,875	207,500
Office rent	4,500	4,500	4,500	4,500	18,000
Office supplies	2,500	2,500	2,500	2,500	10,000
Postage	5,000	5,000	5,000	5,000	20,000
Telephone	9,000	9,000	9,000	9,000	36,000
Travel	4,000	4,000	8,500	8,500	25,000
Printing	3,750	3,750	3,750	3,750	15,000
Promotion	3,750	3,750	3,750	3,750	15,000
Furniture & equipment	10,000	3,000	—	—	13,000
Outside services	3,750	3,750	3,750	3,750	15,000
Contract data base	—	50,000	75,000	75,000	200,000
Contract data entry	—	2,000	4,000	4,000	10,000
Contract funding	—	—	—	100,000	100,000
Miscellaneous	5,000	5,000	5,000	5,000	20,000
Total:	\$98,125	\$143,125	\$171,625	\$291,625	\$704,500
Balance:	\$1,875	\$8,750	\$37,125	\$20,500	\$20,500

## Cash Flow by Quarter: Second Year

	First Quarter	Second Quarter	Third Quarter	Fourth Quarter	Second Year
Cash on Hand	20,500	101,825	126,650	70,475	20,500

## Income:

Inquiries	12,000	30,000	48,000	66,000	156,000
Grants	175,000	100,000	—	—	275,000
Total:	\$187,000	\$130,000	\$48,000	\$66,000	\$431,000

## Expense:

Salary & fringe	51,600	51,600	51,600	73,600	228,400
Office rent	4,950	4,950	4,950	4,950	19,800
Office supplies	2,750	2,750	2,750	2,750	11,000
Postage	5,500	5,500	5,500	5,500	22,000
Telephone	10,000	10,000	10,000	10,000	40,000
Travel	11,250	11,250	11,250	11,250	45,000
Printing	4,125	4,125	4,125	4,125	16,500
Promotion	4,125	4,125	4,125	4,125	16,500
Furniture & equipment	1,500	1,000	—	—	2,500
Outside services	4,125	4,125	4,125	4,125	16,500
Miscellaneous	5,750	5,750	5,750	5,750	23,000
Total:	\$105,675	\$105,175	\$104,175	\$126,175	\$441,200
Balance:	\$101,825	\$126,650	\$70,475	\$10,300	\$10,300

## APPENDIX II.—REPORT OF THE AD HOC COMMITTEE ON FUNDING

## Potential Sources of Funding for National Institute for Computers in Engineering (NICE)

The ad hoc Committee for identifying sources of funds for the NICE Center was constituted June 10, 1980 for the purpose of studying and recommending ways and means of funding the startup of the project, including restrictions. The Committee was also instructed NOT to solicit funds.

The Ad Hoc Committee was made up of:

Mr. Victor N. DiCario, Chairman  
 Dr. Gary Neuwerth  
 Mr. Morton B. Lipetz  
 Mr. J. Crozier Brown

The Committee met June 11, 1980 (copy of minutes attached) and reviewed various potential sources of funds.

A second meeting was held October 13, 1980, in Huntington Beach, California, after receipt of the Business Plan which was being prepared in a parallel effort. Additional contact between the Committee members was accomplished by telephone.

The actual success in any fund-raising activity is heavily dependent upon the personality of the person responsible. It is therefore recommended that a variety

of persons be utilized to provide maximum efficiency in the different fund-raising efforts. Each person should be selected on the basis of willingness to perform fund-raising activity and past experience.

The ability to extract funds from a private corporation is enhanced if a perceived value is attached. It is recommended that two grades of membership in the NICE Center be established, i.e., Founding Sponsors and Charter Sponsors. Founding Sponsors shall be corporations, organizations, or individuals donating substantial capital to NICE, minimum \$10,000. Founding Sponsors shall have an opportunity to have a representative appointed to the NICE Board of Advisors. Charter Sponsors shall be corporations, organizations, or individuals donating between \$5,000 and \$10,000 to NICE.

It is recommended that a Fund-Raising Committee be established with a chairman and sufficient members to cover the areas shown in the following Schedule of Fund Sources:

#### Schedule of Fund Sources

I. Organizations			40,000
A. ASCE		20,000	
B. CEPA		5,000	
C. ICES		5,000	
D. Other organizations		10,000	
II. Direct Solicitation of Private Corporations			205,000
A. Founding sponsors	8 @ 10,000	80,000	
B. Charter sponsors	15 @ 5,000	75,000	
C. Direct contributions	500 @ 100	50,000	
III. Grants			470,000
A. Foundation grants	8 @ 50,000	400,000	
B. Vendor grants		50,000	
C. Others		20,000	
VI. Federal Government			715,000
Total			\$1,430,000

#### Area I: Organizations

The ASCE has taken a leadership role and should be requested to fund a portion of the NICE Center. CEPA and ICES have both indicated support in terms of direct contributions and loans. It is suggested that these organizations could be persuaded to forego the loans and contribute directly. CEPA has already contributed financing in the preparation of the Business Plan. Other organizations such as computer user groups that would derive benefit from NICE should be contacted. A list of these groups is available in the back-up data to the original NICE STUDY and can be obtained from David Schelling at the University of Maryland.

#### Area II: Direct Solicitation of Private Corporations

Due to the nature of persons involved in the NICE proposal, it has always

been assumed that the majority of benefit would be to engineering companies. The Business Plan also relies heavily on engineering-oriented service and references 12,500 engineering firms in the United States and Canada. A logical beginning point would be those firms listed in the ENR 500. Additional lists can be developed thru ASCE and ACEC to cover the remainder. A potential source is also the list of donors to the original NICE STUDY.

### **Area III: Grants**

There are approximately 1,600 Foundations in the United States providing funds for various types of research and development activities (1). These Foundations should be systematically contacted and funds applied for where it is evident that the NICE Center is eligible for grant funds. Vendors should be also contacted in an organized manner and asked to contribute funds in that a large portion of the benefit of NICE will be theirs. Other requires much innovative though and should cover any and all means not covered in Areas I through III.

### **Area IV: Federal Government**

The Federal Government has consistently stressed that an increase in productivity is a desirable national goal. The NICE Center would certainly support this goal, and various governmental agencies should be contacted for funds to match those obtained in Areas I through III.

The obtaining of the Fund-Raising Committee members should be the first act of the NICE Board of Directors and should begin as soon as possible.

### **Minutes—ASCE Ad Hoc Committee for Identifying Sources of Funds for National Institute for Computers in Engineering: June 11, 1980**

The Meeting was held June 11, 1980.

In attendance were:

Mr. Victor N. DeCario, Chairman.

Members:

Mr. J. Crozier Brown

Mr. Morton B. Lipetz

Dr. Gary Neuwerth

Also in attendance were:

Mr. William Luscombe

Mr. Hugh McGrory

Mr. McGrory and Mr. Luscombe explained to Chairman DeCario the proposed functions of the committee, which were to:

1. Identify potential sources of funding for the NICE Center, which were estimated at \$250,000 to \$300,000.
2. There was to be no solicitation of funds at this time.

Mr. Luscombe indicated that a parallel Ad Hoc Committee was preparing a business plan for the NICE Center and that the two plans would be coordinated at the October ASCE Convention in Fort Lauderdale.

Mr. Lipetz suggested three types of funding that should be reviewed:

1. Abnormal funds, which are funds other than normal solicitation.
2. Resources of various organizations.
3. Sale of stock.

Mr. Lipetz also indicated that Control Data Corporation presently has a mechanism for making grants and loans to research or non-profit organizations. He suggested that Mr. Noriss, Chairman of the Board of CDC, be contacted at such time as necessary. Mr. Noriss' interest stems from the amount of time and effort being placed on CDC's emphasis of Technotech.

It has been established that CEPA has pledged a load of \$2,000 and a further load of \$5,000 to the NICE Committee. Terms and conditions to be determined at a later date. ICES has indicated that they may be willing to pledge similar amounts and will be willing to discuss this with the directors of NICE at a future date. Mr. Lipetz indicated that he would follow up with sources of funding through the ASCE.

Mr. Brown indicated that there was a possibility of obtaining funds from the U.S. Waterways Experiment Station and that he would follow up with Mr. Ratach. Mr. McGrory indicated that a United Appeal type of solicitation with personal contact between members of the Solicitation Team and various large corporations could be made. He also suggested a plan based on geographic area would be feasible.

Dr. Neuwerth indicated that he would investigate the tax deduction aspects and what the requirements are so that grants or gifts to NICE would be tax deductible.

Further organizations considered were the American Civil Engineering Council (ACEC), McDonald Douglas Automation, contact Barry Flachsbart. Boeing Computer Services, contact Ted Cook, and the Ford Foundation.

Mr. Brown indicated that he had spoken to Mr. Staats' Liaison person, Harry Mason, of the General Accounting Office. He felt that there was potential for soliciting funds from the Federal Government if the emphasis stresses national improvement of productivity.

Mr. Brown indicated that they may be funds available from the Department of Environment (DOE) if emphasis was placed on conservation of energy. Mr. Lipetz suggested that at various conferences a surcharge could be levied against the conference fee to subsidize NICE. Also, the sale of publications and periodicals and other gimmicks could be used at conferences to generate NICE revenue.

Mr. Lipetz indicated that a potential source of funds may be a pledge of a percent of sales made by vendors, as conference exhibitors, to NICE. Mr. DeCario suggested that a start for the United Appeal may be a list of supports that contributed to the NSF NICE study. He also suggested that perhaps the National Science Foundation would again be willing to contribute funds.

It was also discussed that perhaps colleges and universities would be interested in supporting the NICE Center through the donation of funds and/or services.

Mr. DeCario suggested that perhaps the most efficient way to actually obtain funds would be through the efforts of professional fund raisers. This would then take the effort out of the volunteer stage and put it into the professional arena.

Mr. DeCario adjourned the meeting. Respectfully submitted,

Victor N. DeCario

#### APPENDIX III.—REFERENCES

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2. Reed, E. E., and Garbrecht, M., "1980 Census of Firms," *Consulting Engineer*, June, 1980, pp. 68-78.
3. Staats, E. B., "Computers in Civil Engineering in the World of Today and Tomorrow," Presented at the June, 1980, ASCE Second Conference on Computers in Civil Engineering, held at Baltimore, Md.



# JOURNAL OF THE TECHNICAL COUNCILS OF ASCE

## SEISMIC DESIGN OF LIQUID STORAGE TANKS<sup>a</sup>

By Medhat A. Haroun,<sup>1</sup> A. M. ASCE and George W. Housner,<sup>2</sup> M. ASCE

(Reviewed by the Technical Council on Lifeline Earthquake Engineering)

### INTRODUCTION

Many different configurations of liquid storage tanks can be found in civil engineering applications. However, ground supported, circular cylindrical tanks are more numerous than any other type because they are simple in design, efficient in resisting primary hydrostatic pressure, and can be easily constructed. As the numbers and the sizes of these tanks increased, their behavior under seismic loading became a matter of concern and led to investigations of their vibrational characteristics. The performance of liquid storage tanks during recent earthquakes has revealed more complex behavior than was implied by design assumptions.

Theoretical and experimental investigations of the dynamic behavior of tanks anchored to their foundations were therefore conducted to seek possible improvements in design to resist earthquakes. The results of a finite element analysis of the liquid-shell system (1,2,5) and of the vibration tests of full-scale tanks (2,4) indicated that wall flexibility may have a significant effect on the hydrodynamic pressure induced in these containers. The principal aim of the final phase of the research presented herein is to devise a practical approach which would allow—from the engineering point of view—a simple, fast, and sufficiently accurate, estimate of the seismic response of storage tanks.

A common seismic design procedure for tanks is based on the mechanical model derived by Housner (7) for rigid tanks. A similar mechanical analog, which takes into account the deformability of the tank wall, is developed. It

<sup>a</sup>Presented at the April 14–18, 1980, ASCE Convention and Exposition, held at Portland, Oreg.

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is based on the results of a finite element analysis of the liquid-shell system. The parameters of such a model are displayed in charts that facilitate the calculations of the effective masses, their centers of gravity, and the periods of vibrations. Once the parameters of the mechanical model of the particular tank under consideration are found, the maximum seismic loading can be predicted by means of a response spectrum characterizing the design earthquake.

#### **RIGID CYLINDRICAL TANKS**

Early developments of seismic response theories of liquid storage tanks considered the container to be rigid and focused attention on the dynamic response of the contained liquid.

Housner (7) formulated an idealization for estimating liquid response in seismically excited rigid, rectangular, and cylindrical tanks. He divided the hydrodynamic pressure of the contained liquid into two components: (1) The "impulsive" pressure caused by the portion of the liquid accelerating with the tank; and (2) the "convective" pressure caused by the portion of the liquid sloshing in the tank. The convective component was then modeled by a single degree-of-freedom oscillator. The study presented values for equivalent masses and their locations that would duplicate the forces and the moments exerted by the liquid on the tank. The properties of this mechanical analog can be computed from the geometry of the tank and the characteristics of the contained liquid.

#### **FLEXIBLE CYLINDRICAL TANKS**

The 1964 Alaska earthquake caused the first large scale damage to tanks of modern design and initiated many investigations into the dynamic characteristics of flexible containers. In addition, the evolution of both the digital computer and various associated numerical techniques has significantly enhanced solution capability.

Several studies were carried out to investigate the dynamic interaction between the deformable wall of the tank and the liquid, and showed that the seismic response of a flexible tank may be substantially greater than that of a similarly excited rigid tank. In addition, a study by Veletsos (9) concluded that the impulsive forces in a deformable tank can be reasonably estimated from the solution of a similarly excited rigid tank by replacing the maximum ground acceleration, with the spectral acceleration, corresponding to the fundamental natural frequency of the liquid-tank system.

Despite these efforts, recent developments have not found widespread application in current seismic design codes due to the complexity of computing the dynamic characteristics of tanks. In addition, the lack of experimental confirmation of the theoretical concepts has raised some doubt about the applicability of these methods in the design stage. It should be noted, however, that some codes have recognized the importance of the effects of wall flexibility and adopted an increase in the maximum ground acceleration to an "ad hoc" value representing the short period amplified acceleration due to shell deformation.

## TANK GEOMETRY AND COORDINATE SYSTEM

The tank under consideration is shown in Fig. 1. It is a ground-supported, circular cylindrical, thin-walled liquid container of radius,  $R$ , length,  $L$ , and thickness,  $h$ , with the wall connected to a rigid base. The tank is partly filled with liquid to a height,  $H$ .

A cylindrical coordinate system is used with the center of the base being the origin. The radial, circumferential, and axial coordinates, are denoted  $r$ ,  $\theta$ , and  $z$ , respectively, and the corresponding displacement components of a

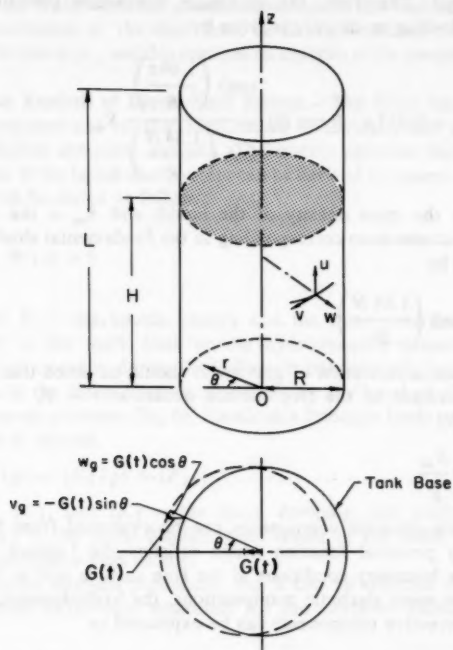


FIG. 1.—Tank Geometry, Coordinate System, and Earthquake Excitation

point on the shell middle surface are denoted by  $w$ ,  $v$ , and  $u$ , respectively. The tank is subjected to a ground motion,  $G(t)$ , in the constant direction of  $\theta = 0$ .

To describe the location of a point on the free surface during vibration, let  $\xi$  measure the superelevation of that point from the quiescent liquid free surface.

## OUTLINE OF METHOD OF ANALYSIS

**Hydrodynamic Pressure.**—The hydrodynamic fluid pressure exerted on the

wall of a deformable tank due to a ground motion,  $G(t)$ , is given by superposition of the long period component contributed by the "convective" fluid motion (sloshing), of the "impulsive" liquid pressure component which varies in synchronism with the horizontal ground acceleration, and of the short period component contributed by the vibrations of the tank wall. In a rigid tank, only the first two components are considered.

It has been shown (2) that the coupling between liquid sloshing modes and shell vibrational modes is weak; and consequently, the convective dynamic pressure can be evaluated with reasonable accuracy by considering the tank wall to be rigid. Therefore, the maximum convective pressure due to the fundamental sloshing mode only is given by

$$|p_s(R, \theta, z)|_{\max} = 0.837 \rho_l R \cos(\theta) \frac{\cosh\left(\frac{1.84z}{R}\right)}{\cosh\left(\frac{1.84H}{R}\right)} S_{as} \quad (1)$$

in which  $\rho_l$  = the mass density of the liquid; and  $S_{as}$  = the spectral value of the pseudo-acceleration corresponding to the fundamental sloshing frequency which is given by

$$\omega_s^2 = \frac{1.84g}{R} \tanh\left(\frac{1.84H}{R}\right) \quad (2)$$

in which  $g$  = the acceleration of gravity. It should be noted that the maximum vertical displacement of the free surface occurs at  $r = R$ ,  $\theta = 0$ , and  $z = H$ ; it is given by

$$\xi_{\max} = 0.837 R \frac{S_{as}}{g} \quad (3)$$

The remaining pressure components can be evaluated from the expression of the velocity potential function which satisfies the Laplace equation, and the appropriate boundary conditions at the free surface and at the liquid-shell interface. After some algebraic manipulations, the hydrodynamic pressure (excluding the convective component) can be expressed as

$$p_d(r, \theta, z, t) = -\frac{2\rho_l}{H} \sum_{i=1}^{\infty} \frac{\int_0^H [\ddot{w}(\bar{z}, t) + \ddot{G}(t)] \cos(\alpha_i \bar{z}) d\bar{z}}{\alpha_i' I_1(\alpha_i R)} I_1(\alpha_i r) \cos(\alpha_i z) \cos(\theta) \quad (4)$$

in which  $\ddot{w}(z, t)$  = the radial component of shell acceleration at  $\theta = 0$ ;  $I_1$  = the modified Bessel function of the first kind of order one; and  $\alpha_i$  = the constants given by

$$\alpha_i = \frac{(2i-1)\pi}{2H} \quad (5)$$

The hydrodynamic pressure exerted on the wall of the tank can therefore be expressed as

$$p_d(R, \theta, z, t) = -\frac{2\rho_f}{H} \sum_{i=1}^{\infty} \left\{ \frac{I_1(\alpha_i R)}{\alpha_i' I_1(\alpha_i R)} \left[ \int_0^H \ddot{w}(\bar{z}, t) \cos(\alpha_i \bar{z}) d\bar{z} + \frac{(-1)^{i+1} \ddot{G}(t)}{\alpha_i} \right] \right\} \cos(\alpha_i z) \cos(\theta) = p_f(R, \theta, z, t) + p_r(R, \theta, z, t) \dots \dots (6)$$

in which  $p_f$  = the hydrodynamic pressure due to the flexibility of the tank wall; and  $p_r$  = the hydrodynamic pressure exerted on the wall of a rigid tank. Clearly the deformation of the shell must be first determined to evaluate the hydrodynamic pressure,  $p_f$ , and this requires an analysis of the coupled liquid-shell system.

**Finite Element Analysis of Liquid-Shell System.**—The finite element method provides a convenient and reliable idealization of the shell and is particularly effective in a digital computer analysis. The matrix equation that governs the seismic response of the liquid-shell system can be derived by means of Hamilton's Principle that can be stated as follows:

$$\delta \int_{t_1}^{t_2} (T - U + W) dt = 0 \dots \dots \dots (7)$$

in which  $T$  and  $U$  = the kinetic energy and the strain energy of the shell, respectively;  $W$  = the work done by the hydrodynamic pressure; and  $\delta$  = a variational operator taken during the indicated time interval.

With the aid of the finite element model of the shell and of the expression of the hydrodynamic pressure (Eq. 6), Hamilton's Principle leads to the following matrix equation of motion

$$[M]\{\ddot{q}\} + [C]\{\dot{q}\} + [K]\{q\} = \{P_{eff}\} \dots \dots \dots (8)$$

in which  $[M]$ ,  $[C]$ , and  $[K]$  = the mass, damping, and stiffness matrices, respectively;  $\{q\}$  = the nodal displacement vector of the shell; and  $\{P_{eff}\}$  = the effective earthquake load vector.

Employing modal analysis procedure, Eq. 8 can be reduced to a system of independent linear differential equations for the unknown modal amplitudes,  $\eta_j$

$$\ddot{\eta}_j + 2\zeta_j \omega_j \dot{\eta}_j + \omega_j^2 \eta_j = -\beta_j \ddot{G}(t) \dots \dots \dots (9)$$

in which  $\omega_j$  and  $\zeta_j$  = the circular natural frequency and the damping ratio, respectively, of the  $j^{\text{th}}$  mode; and  $\beta_j$  = the  $j^{\text{th}}$  modal participation factor.

Once the time history of  $\eta_j(t)$  is obtained, the deformation of the shell can be evaluated, and consequently, the hydrodynamic pressure can be estimated.

#### DERIVATION OF MECHANICAL ANALOG

Consider the mechanical model shown in Fig. 2 in which the effective masses  $m_r$ ,  $m_f$ , and  $m_s$  correspond to the forces associated with ground motion, wall deformation relative to the ground, and liquid sloshing, respectively.

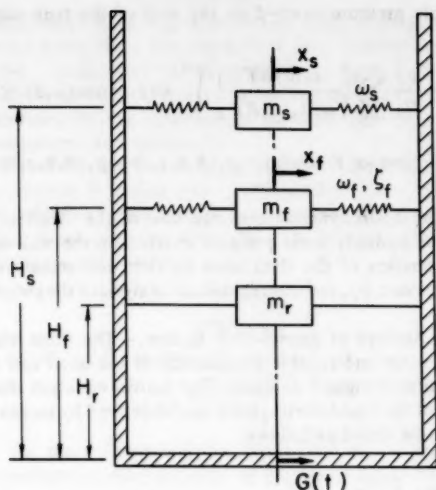


FIG. 2.—Mechanical Model of Flexible Tank

The effective mass,  $m_s$ , can be evaluated from the expression of the hydrodynamic pressure,  $p_s$ , (Eq. 1) by

$$m_s = \frac{\int_0^H \int_0^{2\pi} p_s(R, \theta, z) \cdot R \cos(\theta) d\theta dz}{S_{as}}$$

$$= 0.455 \pi \rho_f R^3 \tanh\left(\frac{1.84 H}{R}\right) \dots \dots \dots (10)$$

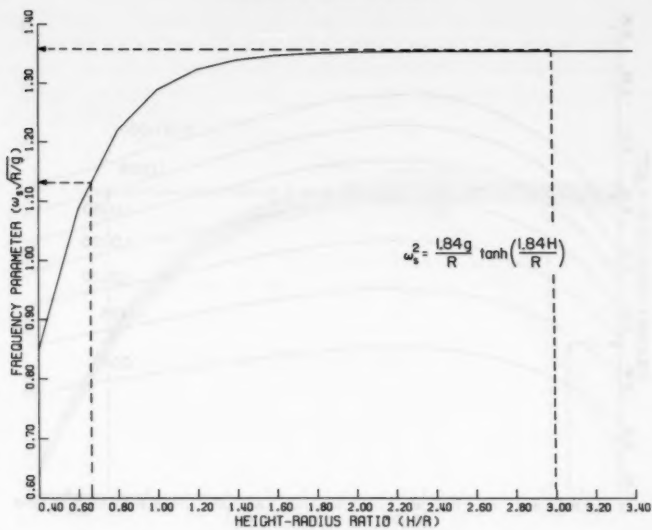
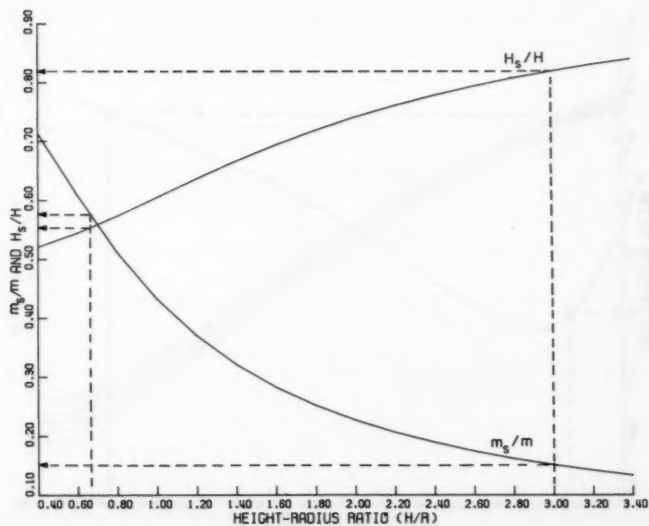
and its center of gravity is at a distance,  $H_s$ , from the base that is given by

$$\frac{H_s}{H} = \frac{\frac{1}{H} \int_0^H z \cosh\left(\frac{1.84 z}{R}\right) dz}{\int_0^H \cosh\left(\frac{1.84 z}{R}\right) dz} = 1 - \left(\frac{R}{1.84 H}\right) \tanh\left(\frac{0.92 H}{R}\right) \dots \dots \dots (11)$$

Fig. 3 presents the values of the nondimensional parameter  $(\omega_s \sqrt{R/g})$  for different values of  $(H/R)$ , while Fig. 4 displays the ratios  $(m_s/m)$  and  $(H_s/H)$  for different ratios of  $(H/R)$  in which  $m$  = the total mass of the liquid.

To evaluate the effective masses,  $m_f$ , and  $m_r$ , one can consider only the fundamental natural mode of vibration of the deformable liquid-filled shell. The nodal displacement vector of the shell can then be written as

$$\{q(t)\} = \{\phi\}_1 \eta_1(t) \dots \dots \dots (12)$$

FIG. 3.—Frequency Parameter,  $\omega_s \sqrt{R/g}$ FIG. 4.—Convective Mass,  $m_s$ , and Its Elevation,  $H_s$

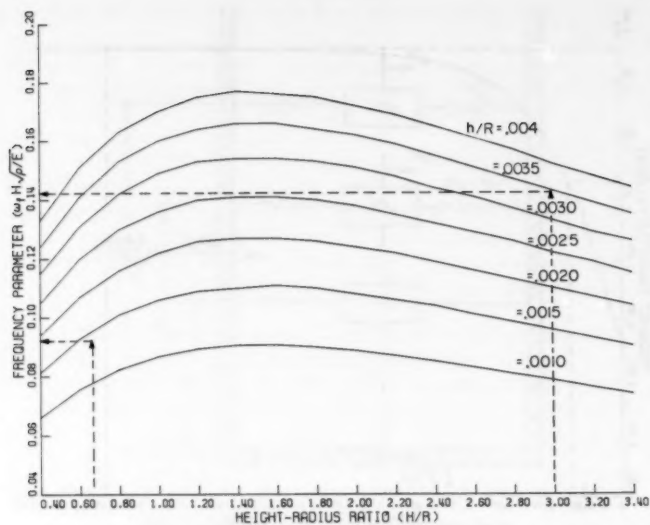


FIG. 5.—Frequency Parameter,  $\omega_f H \sqrt{\rho/E}$

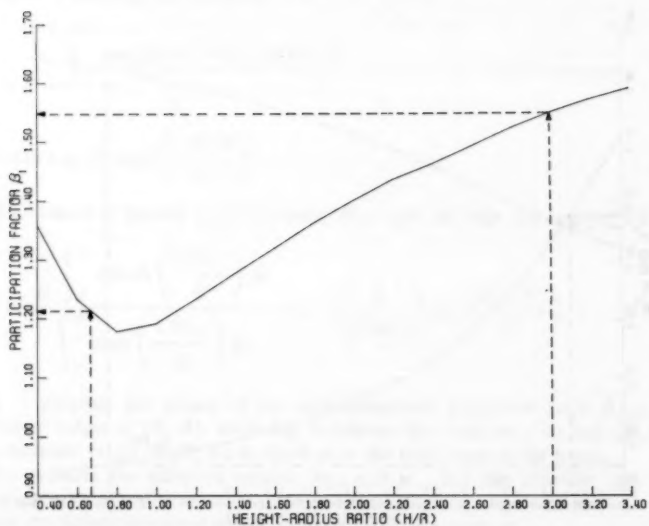
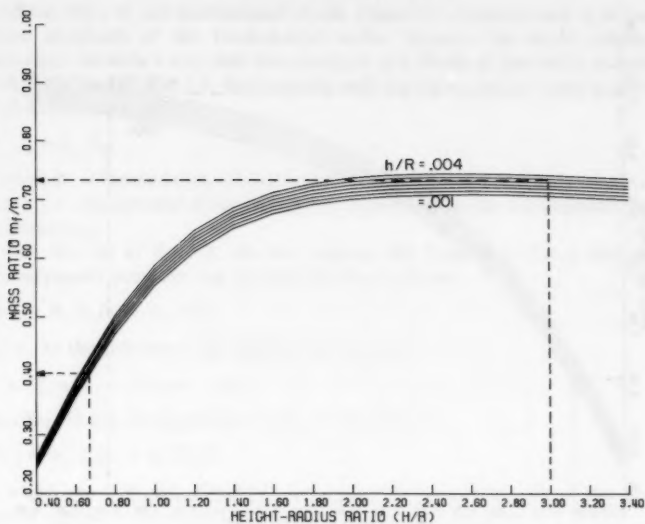
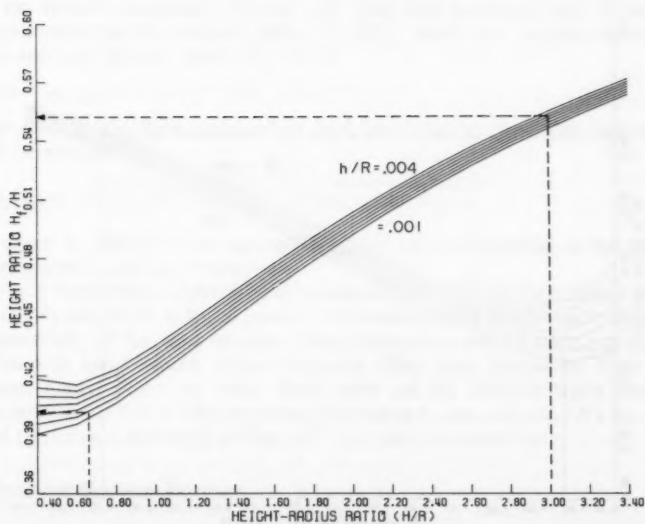
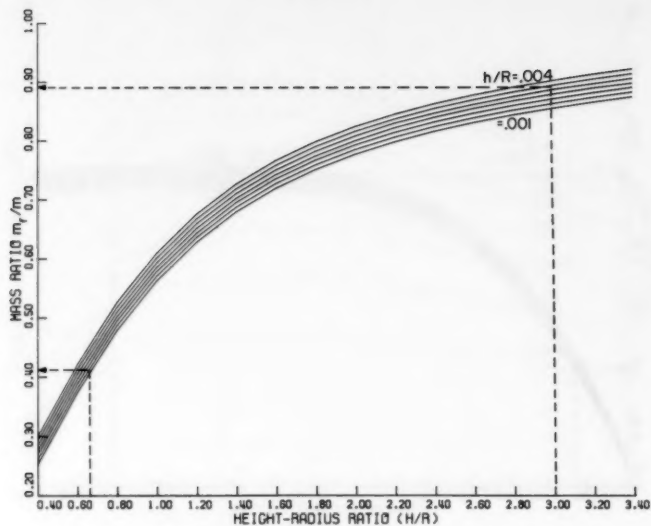
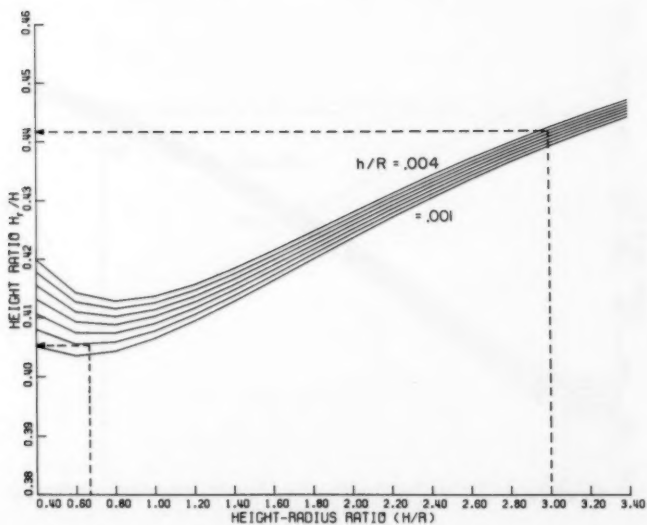


FIG. 6.—Modal Participation Factor,  $\beta_1$

FIG. 7.—Equivalent Mass,  $m_f$ FIG. 8.—Equivalent Height,  $H_f$

FIG. 9.—Equivalent Mass,  $m_r$ FIG. 10.—Equivalent Height,  $H_r$

in which  $\{\phi\}_1$  = the fundamental mode shape of vibration; and  $\eta_1(t)$  = the modal amplitude of the fundamental mode. Because the mode shapes are normalized in such a way that the maximum amplitude of the radial component of shell displacement is 1.0, then one can estimate the maximum radial component of shell displacement by

$$|w_{\max}| = \beta_1 S_{df} \quad (13)$$

in which  $\beta_1$  = the modal participation factor of the fundamental mode of vibration; and  $S_{df}$  = the spectral displacement corresponding to the fundamental natural frequency  $\omega_f$ .

With the aid of Eq. 12, one can express the base shear force (due to the hydrodynamic pressure and the shell inertia force) as

$$Q(t) = \bar{m}_f \ddot{\eta}_1(t) + m_r \ddot{G}(t) \quad (14)$$

Let  $x_f$  be the solution of the differential equation

$$\ddot{x}_f + 2\zeta_f \omega_f \dot{x}_f + \omega_f^2 x_f = -\ddot{G}(t) \quad (15)$$

then Eq. 14 can be expressed more conveniently as

$$Q(t) = m_f \ddot{x}_f(t) + m_r \ddot{G}(t) \quad (16)$$

in which  $m_f = \beta_1 \bar{m}_f$ . Similarly, the overturning moment due to the seismic forces applied to the bottom of the shell can be expressed as

$$M(t) = m_f H_f \ddot{x}_f(t) + m_r H_r \ddot{G}(t) \quad (17)$$

Since the base force and moment due to shell deformability are proportional to the relative acceleration of the shell, one must rearrange Eqs. 16 and 17 before estimating the maximum seismic loads by means of a response spectrum. For example, one can rewrite Eq. 16 as

$$Q(t) = m_f [\ddot{x}_f(t) + \ddot{G}(t)] + [m_r - m_f] \ddot{G}(t) \quad (18)$$

and consequently, the maximum base shear (including the convective component) can be estimated by

$$|Q_T|_{\max} = \sqrt{(m_s S_{as})^2 + (m_f S_{af})^2 + [(m_r - m_f) \ddot{G}_{\max}]^2} \quad (19)$$

in which  $S_{as}$  and  $S_{af}$  = the spectral accelerations corresponding to the natural frequencies  $\omega_s$  and  $\omega_f$ , respectively.

Fig. 5 displays the nondimensional parameter  $(\omega_f H \sqrt{\rho/E})$  for different values of  $(H/R)$  and  $(h/R)$  in which  $\rho$  and  $E$  = the mass density and Young's modulus, respectively, of the shell material. These frequencies are for tanks completely filled with water; similar charts for partly filled tanks completely filled with water; similar charts for partly filled tanks and for different liquid contents can be found in Ref. 3. The remaining parameters  $\beta_1$ ,  $(m_f/m)$ ,  $(H_f/H)$ ,  $(m_r/m)$ , and  $(H_r/H)$  are displayed in Figs. 6, 7, 8, 9, and 10, respectively.

#### ILLUSTRATIVE NUMERICAL EXAMPLES

**Example 1.**—Consider an open top tall tank whose dimensions are:  $R = 24$  ft (7.32 m),  $L = 72$  ft (21.96 m), and  $h = 1$  in. (25.4 mm). The tank is assumed

to be full of water and to be subjected to the North-South component of the 1940 El Centro earthquake.

*Parameters of Mechanical Model.*—The fundamental natural frequency of sloshing can be determined from Eq. 2 (or alternatively from Fig. 3); it is given by

$$\omega_s = \sqrt{\frac{(1.84)(32.2)}{(24)} \tanh\left(1.84 \times \frac{72}{24}\right)} = 1.57 \text{ rad/sec} \quad (20)$$

$$\text{i.e., } T_s = \frac{2\pi}{\omega_s} = 4 \text{ sec} \quad (21)$$

The convective mass,  $m_s$ , (Eq. 10 or Fig. 4) and its elevation,  $H_s$ , (Eq. 11 or Fig. 4) are given by

$$m_s = 0.455 \pi \rho_f R^3 \tanh(5.4) = 3,188 \text{ lb sec}^2/\text{in.} (558.5 \text{ N} \cdot \text{sec}^2/\text{mm}) \quad (22)$$

$$\text{and } H_s = H [1 - 0.181 \tanh(2.76)] = 0.82 H \quad (23)$$

The fundamental natural frequency of vibration of the liquid-filled shell can be determined from Fig. 5 for a value of  $(H/R) = 3.0$  and a value of  $(h/R) = 0.00347$ ; thus

$$\omega_f H \sqrt{\frac{\rho}{E}} = 0.142 \quad (24)$$

$$\text{i.e., } \omega_f = 0.142 \left( \frac{1}{864} \sqrt{\frac{30 \times 10^6}{73.3 \times 10^{-5}}} \right) = 33.25 \text{ rad/sec} \quad (25)$$

$$\text{and therefore } T_f = \frac{2\pi}{\omega_f} = 0.189 \text{ sec} \quad (26)$$

The mass,  $m_f$ , and its location above the base,  $H_f$ , can be evaluated from Figs. 7 and 8, respectively; they are given by

$$m_f = 0.735 m = 0.735 \pi \rho_f R^2 H = 15,555 \text{ lb} \cdot \text{sec}^2/\text{in.} (2,725.1 \text{ N} \cdot \text{sec}^2/\text{mm}) \quad (27)$$

$$\text{and } H_f = 0.554 H = 39.88 \text{ ft} (12.17 \text{ m}) \quad (28)$$

Similarly, the rigidly attached mass,  $m_r$ , and its elevation can be found from Figs. 9 and 10, respectively. Thus

$$m_r = 0.892 m = 18,877 \text{ lb} \cdot \text{sec}^2/\text{in.} (3,307.3 \text{ N} \cdot \text{sec}^2/\text{mm}) \quad (29)$$

$$\text{and } H_r = 0.442 H = 31.82 \text{ ft} (9.71 \text{ m}) \quad (30)$$

*Spectral Values.*—The maximum ground acceleration of the N-S component of the 1940 El Centro earthquake is 0.348 g. The spectral acceleration,  $S_{as}$ , corresponding to the sloshing frequency,  $\omega_s$ , and for a damping ratio,  $\zeta_s$ , of 0.5% can be found from the response spectrum; it is given by  $S_{as} = 0.063$  g. Lastly, the spectral displacement and acceleration corresponding to the frequency,  $\omega_f$ , and for a damping ratio of 2% are  $S_{df} = 0.298$  in. (7.57 mm), and  $S_{af} = 0.856$  g.

## Seismic Response

1. Maximum Wave Height.—Using Eq. 3, the maximum free surface displacement is given by

$$\xi_{\max} = 0.837(288)(0.063) = 15.19 \text{ in. (386 mm)} \quad (31)$$

2. Maximum Shell Displacement.—Employing Fig. 6, the modal participation factor is 1.55; and consequently, the maximum radial component of shell displacement is given by Eq. 13

$$|w_{\max}| = \beta_1 S_{df} = (1.55)(0.298) = 0.462 \text{ in. (11.7 mm)} \quad (32)$$

3. Maximum Base Shear.—Using Eq. 19, the maximum base shear can be estimated by

$$\begin{aligned} |Q_T|_{\max} &= \sqrt{[(3,188)(0.063)(386.4)]^2 + [(15,555)(0.856)(386.4)]^2 + [(3,322)(0.348)(386.4)]^2} \\ &= 51.65 \times 10^5 \text{ lbs (22.98} \times 10^6 \text{ N)} \quad (33) \end{aligned}$$

4. Maximum Overturning Moment (and Maximum Axial Stress).—The maximum overturning moment applied to the bottom of the shell is given by

$$\begin{aligned} |M_T|_{\max} &= \sqrt{(m_s H_s S_{as})^2 + (m_f H_f S_{df})^2 + [(m_s H_s - m_f H_f) \ddot{G}_{\max}]^2} \\ &= 205.3 \times 10^6 \text{ lb} \cdot \text{ft (278.6} \times 10^6 \text{ N} \cdot \text{m)} \quad (34) \end{aligned}$$

and consequently, the maximum axial stress at the bottom of the shell is given by

$$\sigma_z|_{\max} = \frac{|M_T|_{\max}}{\pi R^2 h} = \frac{205.3 \times 10^6 \times 12}{\pi (288)^2 (1)} = 9,454 \text{ lb/in.}^2 (65,138 \text{ kPa)} \quad (35)$$

5. Maximum Hoop Force Resultant.—Assuming that the hydrodynamic pressure is uniformly distributed along the shell height, the maximum hoop force

TABLE 1.—Impulsive Earthquake Response of Tall Tank (Input: N-S Component of 1940 El Centro Earthquake)

Variable (1)	Mechanical model (2)	"Exact" solution (2) (3)	Rigid tank (7) (4)
Fundamental period, $T_f$ , in seconds	0.189	0.188	—
Maximum shell displacement, $w_{\max}$ , in inches (millimeters)	0.462 (11.7)	0.445 (11.3)	—
Maximum base shear, $Q_{\max}$ , in pounds (newtons)	$51.65 \times 10^5$ ( $22.98 \times 10^6$ )	$51.08 \times 10^5$ ( $22.7 \times 10^6$ )	$27.18 \times 10^5$ ( $12.1 \times 10^6$ )
Maximum axial stress $\sigma_z _{\max}$ , in pounds per square inch (kilopascals)	9,454 (65,138)	8,375 (57,704)	3,444 (23,729)
Maximum hoop force resultant $N_{\theta} _{\max}$ , in pounds per inch (newtons per millimeter)	1,903 (333.4)	2,166 (385.3)	1,417 (248.3)

resultant at the base of the tank can be approximately estimated by

$$N_{\theta}|_{\max} = p_d \cdot R = \frac{Q}{\pi R H} \cdot R = \frac{Q}{\pi H} = 1,903 \text{ lb/in. (333.4 N/mm)} \quad (36)$$

**Comparison with "Exact" Solution.**—Table 1 shows a comparison between the maximum response values obtained by the simplified mechanical model using the response spectrum of the record, and those found by time integration of the modal equations of motion and superposition of four modes; it also displays those for a similarly excited rigid tank (note that, for the particular tank under consideration, the contribution of the convective forces is negligibly small as compared to the effect of the impulsive forces).

**Example 2.**—The design charts are also used to estimate the earthquake response of an open top, fixed base, broad tank whose dimensions are:  $R = 60 \text{ ft (18.3 m)}$ ,  $L = 40 \text{ ft (12.2 m)}$ , and  $h = 1 \text{ in. (25.4 mm)}$ . The tank is assumed to

TABLE 2.—Seismic Response of Broad Tank

Parameters	$T_s$ (sec)	$T_f$ (sec)	$m_s$	$m_f$	$m_r$	$H_s$	$H_f$	$H_r$
			lb. sec <sup>2</sup> /in			Feet		
		6.89	0.162	42227	29761	30496	22.2	16.04
Spectral Values	$S_{as} = 0.028 \text{ g}$		$S_{af} = 0.828 \text{ g}$			$S_{df} = 0.214 \text{ in}$		
Seismic Response	$\xi_{\max} = (0.837)(720)(0.028) = 16.88 \text{ in}$					Exact Solution		
	$w_{\max} = (1.21)(0.214) = 0.259 \text{ in}$					0.244 in		
	$Q_{\max} = 95.33 \times 10^5 \text{ lbs}$					$89.22 \times 10^5 \text{ lbs}$		
	$\sigma_z _{\max} = 1128 \text{ lb/in}^2$					1085 lb/in <sup>2</sup>		

be full of water and to be subjected to the N-S component of the 1940 El Centro earthquake.

Following the same procedure as in example 1, one can estimate the maximum response of the tank; the results are displayed in Table 2. It should be noted that, in a broad tank, the maximum amplitude of the radial component of shell acceleration occurs near the bottom of the tank not at the top as in tall tanks.

#### REMARKS

1. The foregoing analysis is applicable *only* to tanks that are anchored to a rigid base. The support of an unanchored tank can resist downward forces while the uplift of the tank is prevented only by the dead weight of the tank and its content. As soon as any vertical tensile stress, induced by earthquake motion, exceeds the stress due to the dead load, uplift will occur; and consequent-

ly, one cannot assume the tank to be cantilevered from its base.

2. The effect of shell mass on the fundamental natural frequency of full tanks can be neglected; consequently, one can estimate the natural frequency,  $\bar{\omega}_f$ , of a tank filled with liquid of density,  $\rho_f$ , by

$$\bar{\omega}_f = \omega_f \sqrt{\frac{\rho_w}{\rho_f}} \dots \dots \dots (37)$$

in which  $\omega_f$  = the natural frequency of the same tank when filled with water; and  $\rho_w$  = the mass density of water.

## CONCLUSION

A mechanical model, which takes into account the deformability of the tank wall, is developed and its parameters are displayed in charts. The maximum seismic response of an anchored deformable tank can therefore be estimated by means of a response spectrum. Comparison with the "exact" solution of the problem confirms the validity of the method.

## ACKNOWLEDGMENT

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## APPENDIX II.—NOTATION

*The following symbols are used in this paper:*

- $[C]$  = damping matrix;
- $E$  = Young's modulus of shell material;
- $G(t)$  = ground motion;
- $g$  = acceleration of gravity;
- $H$  = liquid depth;
- $H_f, H_r$ , and  $H_s$  = elevations of effective masses;
- $h$  = shell thickness;
- $I_1$  = modified Bessel function of first kind of order one;
- $[K]$  = stiffness matrix;
- $L$  = shell length;
- $[M]$  = mass matrix;
- $M(t)$  = overturning moment;
- $m$  = total mass of liquid;
- $m_f, m_r$ , and  $m_s$  = effective masses associated with shell deformation, ground motion, and liquid sloshing, respectively;
- $N_\theta$  = hoop force resultant;
- $\{P_{eff}\}$  = effective earthquake load vector;
- $p_d$  = hydrodynamic pressure;
- $p_f, p_r$ , and  $p_s$  = hydrodynamic pressure components;
- $Q(t)$  = base shear force;
- $\{q\}$  = nodal displacement vector of shell;
- $R$  = tank radius;
- $r$  = radial coordinate;
- $S_{af}$  and  $S_{df}$  = spectral acceleration and displacement, respectively;
- $S_{as}$  = spectral acceleration of convective motion;
- $T$  = kinetic energy of shell;
- $T_f$  and  $T_s$  = fundamental periods of vibration of liquid-filled shell and of liquid sloshing, respectively;
- $t$  = time;
- $U$  and  $W$  = strain energy of shell and work done by hydrodynamic pressures, respectively;
- $u, v$ , and  $w$  = shell displacement components in axial, circumferential, and radial directions, respectively;
- $x_f$  = solution of Eq. 15;
- $z$  = axial coordinate;
- $\alpha_i$  = constants, Eq. 5;
- $\beta_j$  = modal participation factors;
- $\delta$  = variational operator;
- $\zeta_j$  = damping ratios;

- $\eta_j$  = modal amplitudes;
- $\theta$  = circumferential coordinate;
- $\xi$  = free surface displacement;
- $\rho, \rho_s$ , and  $\rho_w$  = mass density of shell, liquid, and water, respectively;
- $\sigma_z$  = axial stress;
- $\{\phi\}_1$  = fundamental mode shape;
- $\omega_f$  and  $\bar{\omega}_f$  = fundamental frequency of vibration of liquid-filled shell;
- $\omega_j$  = circular natural frequencies; and
- $\omega_s$  = fundamental frequency of liquid sloshing.



# JOURNAL OF THE TECHNICAL COUNCILS OF ASCE

## DISCUSSION

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Figures supplied by the discussor should be designated by letters, starting with A. This also applies separately to tables and references. In referring to a figure, table, or reference that appeared in the original paper/technical note use the same number used in the original.

It is suggested that potential discussors request a copy of the *ASCE Authors' Guide to the Publications of ASCE* for more detailed information on preparation and submission of manuscripts.

## APPROACHES TO PROGRAM CORRECTNESS<sup>a</sup>

Closure by Joseph O. Harrison, Jr.<sup>3</sup>

The writer wishes to thank the discussor, T. K. Chaplin, for his interest in the paper and for his penetrating observations on the nature of engineering computing. He has pointed out, quite correctly: (1) That engineering calculations are concerned for the most part with relationships among real variables while the computer deals only with digital approximations to them; and (2) that this fact gives rise to a number of problems related to the correctness of computer programs.

Numerical solutions to engineering problems may be conveniently thought of as involving three processes: model-making, numerical analysis, and programming.

The *model-making process* is devoted to describing by mathematical relationships the significant attributes of the physical entity that is the object of the engineer's attention. Mathematical models do not generally describe the entity completely, but only those aspects that are pertinent to the problem at hand, and further to describe even these aspects only to the precision required for an adequate solution.

Consider, e.g., a projectile in flight. A frequently used mathematical model is the set of differential equations derived from the assumption that the projectile is a particle subject to various forces acting in accordance with Newton's Laws. The model will predict the range of an artillery shell's trajectory in terms of its initial angle and velocity to an accuracy of five or more significant figures, which is ample for the construction of firing tables. The same model is inadequate however for determining design characteristics such as rate of spin that influence the shell's stability.

The *numerical analysis process* consists of specifying numerical algorithms and procedures for solving the model's equations. In the case of the artillery shell trajectory, the differential equations would be replaced by the Runge-Kutta formulas or some other algorithm for solving systems of ordinary differential equations.

Numerical algorithms do not "solve" mathematical equations in the strict sense, but only provide approximations to their solutions. The approximations may, however, with some exceptions, be made as accurate as desired. The accuracy is achieved by controlling features such as: (1) The number of significant figures to which arithmetic operations are carried; (2) the numbers of terms of infinite series; (3) the numbers of iterations of repetitive algorithms; and (4) the step and grid sizes in space-time relationships and the like.

The exceptions occur in regions of instability. Sometimes the errors of

<sup>a</sup>November, 1978, by Joseph O. Harrison, Jr. (Proc. Paper 14146).

<sup>3</sup>Sr. Scientist for Computer Science, Inst. for Computer Sci. and Tech., National Bureau of Standards, U.S. Dept. of Commerce, Washington, D.C. 20234.

approximation accumulate to the extent that the amount of arithmetic necessary to achieve the required accuracy is impractical. In such a case, a different algorithm must be used, or if the instability is rooted in the model itself, a new approach to solving the problem has to be found.

In any event, the output of the numerical analysis process is the specification of a suitable computational algorithm together with the numerical values of those parameters that control the accuracy of the results. The substitution of decimal approximations for real numbers is accomplished at this point.

The *programming process* encompasses all of the activities needed to construct a code that faithfully follows the specifications developed by the numerical analysis process.

In practice, the partitioning of a computational problem into the processes of model making, numerical analysis, and programming is seldom as clear cut as this description would indicate, particularly if the same person works on all three processes. Nevertheless, the three process breakdown will serve as a framework for the closing points that the writer wishes to make.

First, the material in the original paper is in no way restricted to discrete variable problems such as are usually encountered in financial and administrative data processing. It is equally applicable to engineering problems formulated in terms of continuous variables. It is however addressed only to the programming part of such problems. Numerical analysis is recognized as a separate discipline in its own right. This recognition is consistent with the way in which the term "program correctness" is used in the programming literature.

Second, the term "correctness" applies only to the programming process. It is, as the discussor has noted, a doubtful concept to apply to the model making and numerical analysis processes. Perhaps one should speak instead of the *appropriateness* of a mathematical model and the *adequacy* of a numerical approximation to it.

Finally, a responsible engineer must view program correctness in the context of the overall problem solving process. He should accept the analytic methods of the three subprocesses for what they have to offer him. But over and above this, he must, as he has always done, check the overall results by every means at his disposal including the performance of real life tests, the construction and testing of prototypes, the comparison with similar cases and the use of informed engineering judgement.

## ETHICAL CONSIDERATIONS IN COMPUTER USE\*

Discussion by Gregory J. Dick,<sup>1</sup> A. M. ASCE

The paper is, in fact, the writer's first exposure to a substantial commentary on such ethical considerations in computer use. That is, it presents something beyond passing acknowledgment to the subject which is seen in the context of other discussions on computer use, professional ethics, quality assurance, etc. This report does a creditable job within its stated objectives.

The writer's experience in the development, support, and use of computer applications for civil engineering suggests that caution and reflection on the several points put forth are worthwhile. It is worthwhile, not from a stance of alarm, but from the perspective of responsible concern. The writer is pleased with an affirmation of the principle that the use of computers does not alter the traditional professional responsibility to clients or the general public. When their use is appropriate, the competent and efficient application of computer programs is to be expected. How one is to insure proper usage is another matter.

The evolution from simple, single-purpose computer programs to an ever more complex integration of capabilities continues. Such comprehensive systems do challenge any given engineer's resources to thoroughly validate and check them. However, this challenge is only one of many activities to which professional ethics requires a thoughtful response. The paper offers several sound suggestions and approaches. It is perfectly reasonable to modify these suggestions in regard to one's particular circumstance.

In this regard, the writer will add the following comment. More attention should be given to the fact that documentation is very important. This is true whether the computer services are obtained in-house or not. Yet, engineer's often find themselves provided with pitiful aids. The documentation for a computer program must define the type and format of input data. This information may be emphasized to the detriment of the explanation of the program's assumptions, modeling techniques or interpretation of output results. Many times a program's documentation fails to clarify the algorithms used and related limitations.

A sincere demand from engineers for better documentation would be heard. It is difficult to imagine in the context of this discussion the use of any computer program without appropriate documentation.

The paper states that to some engineers the computer may present certain temptations. These temptations are not unethical in themselves. Therefore, the implication that this situation will continue presents no particular problem. Professionals who have satisfactorily addressed themselves to their ethical responsibility in this matter will no doubt continue to do so. Whether others,

\*December, 1979, by the Computer Practices Committee of the Technical Council on Computer Practices (Proc. Paper 15056).

<sup>1</sup>Sr. Consultant, McDonnell Douglas Automation Co., Box 516, St. Louis, Mo. 63166.

who may have fallen prey to these temptations, will reassess their actions (or inactions) in light of the paper's discussion is questionable.

In closing, the writer believes it to be prudent for engineers to examine their present practice in regard to computer use. It would be beneficial to professionals to explicitly satisfy themselves that their mode of operation meets the spirit of ethical computer use. Some engineers may find this difficult in their particular environment. Again, this in no way reduces the professional responsibility to meet established ethical standards.

#### **Discussion by the CEPA Review Committee of the Society for Computer Applications in Engineering, Planning, and Architecture**

The responses of the CEPA review committee to the original paper were varied. While some committee members expressed complete endorsement without reservation, others felt that the manner in which the paper was presented was potentially dangerous and could possibly lead to the diminished use of computers by the engineering profession.

The basic premise of the paper is timely. Computers have become an integral part of the operations of many engineering firms, a trend which is expected to increase as the cost of computer power decreases through technological advances.

By using a computer, the practicing professional engineer can augment his ability in his particular area of expertise. He may investigate a larger number of alternate solutions and he may work with techniques that were previously too cumbersome to do manually. It would be rather simplistic to state that the engineer is acting unethically when he utilizes computer programs totally outside his area of expertise. The danger occurs, as this paper well states, when the engineer attempts to extend his ability or misrepresent his ability because of access to computer software.

It was generally agreed by the reviewers that the engineer should be familiar with a computer program before he attempts to utilize it. Through an education process, he should be able to understand the input to the program, the solution techniques employed by the program, the range of problems to which the program is applicable, and most importantly he should be able to rely on his professional experience to evaluate the output from the computer. It was stated in the paper that "Colleges, universities, professional societies . . . offer excellent training courses in modeling techniques and application programs, thereby providing ample opportunity for training and education." The CEPA NICE proposal contradicts this statement as follows, "The practicing engineer is offered few opportunities to improve his knowledge of computers through university instituted continuing education. . . ." This is not a major problem, however, since on-the-job training is recognized by many practitioners as being far more effective than short courses available through any of the aforementioned groups. The reviewers recognize that both education of the engineer and validation of the computer program by the engineer, prior to its use, are essential steps in computer-aided engineering analysis. As was well stated in the paper, the engineer's responsibility, both legally and professionally, does not change just

because he has utilized a computer in arriving at his solution.

It is the method by which the engineer assures himself that a program is valid for use on his particular application that is of concern to some members of the review committee. It is felt that his validation process should be commensurate with the potential liability of the application. One would not expect the validation process applied to a computer program used for calculating earthwork volumes to be as extensive as that applied to a computer program used for earthquake analysis of multistoried buildings. The ramifications of an error in the latter program would be far more severe than that resulting from an error in the former program. To imply, by omission, that rigorous validation procedures be applied uniformly to all computer software could result in diminished use of computers by the practicing engineer in order to avoid burdensome validation costs.

While the authors state in the conclusion that the guidelines presented can be used on small-scale computer programs developed inhouse but might need to be modified for large-scale computers, no attempt is made to correlate the validation procedure to the seriousness of the applications.

Potential misuse of this paper might be found in the legal arena. While we are sure that the authors did not intend for this paper to be used as a cudgel by lawyers against the professional engineer who has diligently used the computer to improve his practice and still made an error, we see the extensive detailing of ways to double-check work as being risky. In these days of rampant litigation, failure to take *all* of the checking approaches mentioned might be construed as negligence on the part of the engineer.

This paper has raised some lofty questions, questions which need to be recognized. It does prompt responsible individuals to reflect on the manner in which they are using the computer and the ramifications of misuse of the computer. To this end, the paper is very well written and adequately covers the concerns described in the title.

If, however, the paper is intended to serve as a guideline to attempt to *insure* ethical use of computers by the engineering community, it falls far short. Too little history exists as yet for such an attempt and premature restrictive guidelines may place computer usage in a box from which it might never escape.

We feel that the following changes to the text of the paper would eliminate most of the reservations that have been expressed by the CEPA Review Committee:

1. Page 415, paragraph 2, after sentence 2 ending "legal responsibilities," replace sentence 3 with insertion

It should be recognized, however that this paper is only a beginning. There has not as yet been sufficient history of computer use on engineering applications to formulate "cast in stone" guidelines on ethical computer use. This paper is only intended to prompt the practicing professional to be cautious and to anticipate possible ramifications that could result from computer use.

2. Page 416, final sentence in definition of term "Truncation error," change the word "invalid" to "inexact."

Purpose: The degree of accuracy found in a problem solution is only as good as the accuracy of the input data. Using 0.3333 may be just as valid as 0.333333. . . . The word "invalid" in this sentence is far too strong.

3. Page 418 paragraph 3 delete the sentence:

Often, too much reliance is put on computer-generated results and not enough on common sense.

Purpose: This statement is too severe and is unfair to the profession. It makes it seem as if engineers are in the habit of using computers irresponsibly.

4. Page 419, paragraph 4, after "service bureau," add

The effort involved in the validation process should be commensurate with the potential liability of the application. One would expect the validation process applied to a computer program to be used for earthwork calculations would be far less extensive than that applied to a computer program for earthquake analysis of multistoried buildings. The ramifications of an error in the latter program would be far more severe than an error found in the former program.

5. Page 420, paragraph 1, replace "must assure" with "should assure."

Purpose: This paper is intended as a guideline, not a set of hard and fast rules, such as "must" implies.

6. Page 420 paragraph 3, delete the following sentence:

In doing so, they have accepted the fact that the use of a computer, application software, or computer services is at their own risk.

Purpose: This sentence implies that computers give "wrong answers." It makes as much sense as saying, "The engineer accepts the fact that the use of a slide rule is at his own risk."

7. Page 425, paragraph 5, sentence 4, replace "inevitably contain" with "might contain."

Purpose: The statement as originally written implies that errors *will* be encountered if large-scale computer programs are used. This statement is not necessarily true.

8. Page 426, Under "Conclusions," after last sentence, add

Hopefully, this paper has stimulated some thought on the professional and ethical use of computers on engineering applications. As more history

on this subject becomes available, more definitive guidelines can be prepared to address the many levels of computer applications available to the engineering community.

This discussion was respectfully submitted by the CEPA review committee of the Society for Computer Applications in Engineering, Planning, and Architecture. Committee Members:

Victor N. DeCario  
Michael R. Eiben  
Robert Kenngott  
William C. Luscombe  
Andrew Machen  
Joseph C. Rodgers  
Joseph P. Harrison  
John Crane  
Donald M. Pries  
Gary E. Neuwerth, Chairman

**Discussion by M. Llewellyn Thatcher,<sup>2</sup> M. ASCE**

The writer would like to express his appreciation to the authors for their efforts to confront such difficult and most important issues. These issues are crucial to the engineering and scientific communities which find themselves dealing with a new tool whose power can be easily abused by a lack of attention to the ethical responsibilities such as those brought out by the authors.

The writer would like to discuss some of the problems of validation of software in the field of hydrodynamics and mass transport in rivers and estuaries.

Computer programs in this field are plentiful, but except for very simplified prototype conditions, validation is not readily achievable. This stems from the facts that first, the techniques for solving the analytical problem in terms of governing equations are essentially those of numerical solutions to nonlinear partial differential equations with variable coefficients and second, the collecting of data in the prototype waterbody for calibration and verification is in itself a major undertaking. This second problem is responsible for a multiplicity of poorly validated and relatively unverified computer programs for analyzing hydrodynamic and mass transport behavior. Such programs may be correctly written, but the user has the responsibility to show that it is a *valid* tool for his application. The five methods proposed by the committee are relevant but each method has its limitations as presented in Table 1.

There is a fundamental problem in computer modeling of hydrodynamics and mass transport with respect to the model's *capability of predicting*. A model may be well validated with respect to its programming and input-output relationships, but may be unsuitable for predicting flows or water quality concentrations in applications wherein the geometry of the waterbody or the boundary conditions

<sup>2</sup>Vice Pres., Najarian, Thatcher & Assoc., Inc., 294 Harrington Ave., Closter, N.J. 07624.

are distinct from those used to calibrate the various coefficients of the model. The user of these models must be aware of their limitations and not be lulled into a false sense of security by beautiful plotting programs which display the model's response to its input data.

It is incumbent upon the individual responsible for the use of a computer model to point out those areas wherein the model's capability to predict is

**TABLE 1.—Limitations of Validation Methods with Respect to Hydrodynamic and Mass Transport Programs**

Validation method (1)	Limitation with respect to hydrodynamic and mass transport programs (2)
Comparison of results with classical solutions, experimental test data, or analytical results published in technical literature.	Only simplified geometric domains, dispersive relationships, and boundary conditions are amenable to analytical solutions. Experimental test data limited by conditions of physical hydraulic modeling such as artificial roughness strips which give validation only for Reynolds numbers and dispersive conditions of the physical model (usually a dimensionally distorted model).
Comparison of results with another program which employs a different mathematical model or numerical techniques to solve the same problem.	Applications of hydrodynamic and mass transport programs tend to be expensive which make consultants reluctant to apply two models to the same problem. Due to the many different assumptions in different models, it may be difficult to explain different results from different models. It may be even more difficult to discern which result is <i>better!</i>
Comparison of results with another program used to solve the same problem, using the same mathematical model, but developed by an independent person, group, or organization.	This method will be limited to the simpler problems (such as Streeter-Phelps solutions) which have been programmed by different people. The size and cost of development of most hydrodynamic and mass transport programs makes duplication unlikely. (Not to mention "unpopular" to sponsoring government agencies.)
Comparison of results with manual calculations.	This method is limited only by the expense and time required by manual calculations. For numerical solutions to the governing partial differential equations, the method cannot be practical for complete validation.
Checking of results to determine reasonableness when the programs perform no analytical calculations (such as plot programs).	Highly recommended for <i>all</i> programs, including those performing analytical calculations.

limited. This can be done only if the model user has: (1) The qualification and training with the tool necessary for its application; and (2) the willingness to discuss the model's limitations in a frank, unbiased way. This second requirement is often difficult to meet due to the pressures of competition. The writer urges clients for such hydrodynamic and mass transport studies to insist

on more candor and completeness in the discussion of a model's ability to make predictions. Details to be included in such discussions should include the effect of any spatial and temporal averaging of the governing equations and, assumptions related to frictional and dispersive relationships. Failure to deal with this aspect of computer modeling creates the "Black Box" solution to problems mentioned by the authors.

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### ESTABLISHING A COMPANY COMPUTER NETWORK<sup>a</sup>

**Errata.**—The following corrections should be made to the original paper:

Page 363, paragraph 2, line 2: Should read "PDP 11/70 computer" instead of "PDP 11/73 computer"

Page 366, paragraph 3, line 4: Should read "The search began with the vendors of conventional RJE terminals." instead of "The search began with the vandors of conventional RJE terminals."

Page 366, paragraph 6, line 3: Should read "the primary peripheral device for the operating system." instead of "the primary petripheral device for the operating system."

Page 367, paragraph 2, line 2: Should read "any data file residing on the Miami terminal" instead of "any data file residing on the Miani terminal"

Page 367, paragraph 5, line 5: Should read "the operating system and its procedures." instead of "the operation system and its procedures."

Page 368, paragraph 5, line 2: Should read "having a mix of transmission speeds," instead of "having a max of transmission speeds,"

Page 368, paragraph 5, line 4: Should read "multiplexers will allow six to eight" instead of "multiplexers will alow six to eight"

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<sup>a</sup>December, 1979, by Glenn S. Orenstein (Proc. Paper 15080).

## URBAN RUNOFF QUALITY: INFORMATION NEEDS\*

Discussion by William Whipple, Jr.<sup>2</sup>

The challenging paper by the author strikes at the heart of our national water quality problem. Without an adequate understanding of urban runoff, how can we be sure that the vast expenditures on waste treatment are justified, or will achieve their environmental objectives? The author has boldly exposed, and in some cases exaggerated, the conceptual inadequacies, pretentious intellectual facades, and poor factual foundation of much of the current theory on urban runoff. Unfortunately, most of this iconoclastic cynicism is all too true. The writer, after struggling with these problems for some 12 yr, and reading extensively from the literature, cannot pretend to have available the scientific knowledge which Sonnen feels we should have.

The opinion of the writer is that the author has demanded too much of the profession. There are many subjects which can be understood and dealt with on a more or less empirical basis, even though the full scientific basis for understanding them is not available. Most of the practice of medicine still falls in this category, e.g., despite the many decades during which a full scientific understanding has been sought. For urban runoff pollution we have had only one decade of priority attention.

Being a practitioner, as well as a theorist, in the field of urban runoff evaluation and control, the writer is not unduly disturbed by the manifest inadequacies in the detailed mathematical models which concern the author so deeply. The lack of data is more important to the practitioner; but for practical applications rather basic information, not necessarily related to a full scientific context, is of first priority.

It is somewhat misleading to say, as the author does, that the importance or insignificance of urban runoff as a source of damaging pollution is going undiscovered. This is true only in the context of the full mathematical modeling approach explained in the original paper. Less refined data gathering and analysis make it apparent that urban streams such as the West Branch Shabakunk in Trenton and Mile Run in New Brunswick, N.J., are seriously polluted, even though they have no point sources subject to the official control program. It is definitely established that part of the pollution in such streams comes from housing (the more densely occupied the more polluted), that sanitary sewer overflows contribute materially, and that a great deal of pollution in "urban runoff" comes from small commercial and industrial establishments, both as true runoff and as discharges, leaks, spills and seeps. While much better information would be useful, we know enough to approximate the contributions

\* August, 1980, by Michael B. Sonnen (Proc. Paper 15611).

<sup>2</sup> Research Prof., Rutgers Univ., Water Resources Research Inst., Office of the Dir., Cook Coll. Campus, P.O. Box 231, New Brunswick, N.J. 08903; also, Consultant, Delaware and Raritan Canal Commission, N.J.

from these various sources for the common pollutants, in any case we are able to investigate.

What is of particular concern is that outside of a few research papers (25) there is practically no information on petroleum hydrocarbons, which is probably more serious as a pollutant of small urban streams than all the other common pollutants combined, especially since lead is on the way down as a pollutant, due to unleaded gasoline. Also, totally inadequate attention has been given to bacterial and viral pathogens and to various organic toxics.

We already have enough information to know the following:

1. In established urban areas, a remedial approach to treatment of urban runoff is very expensive and can be economically justified only under extraordinary circumstances, if at all.

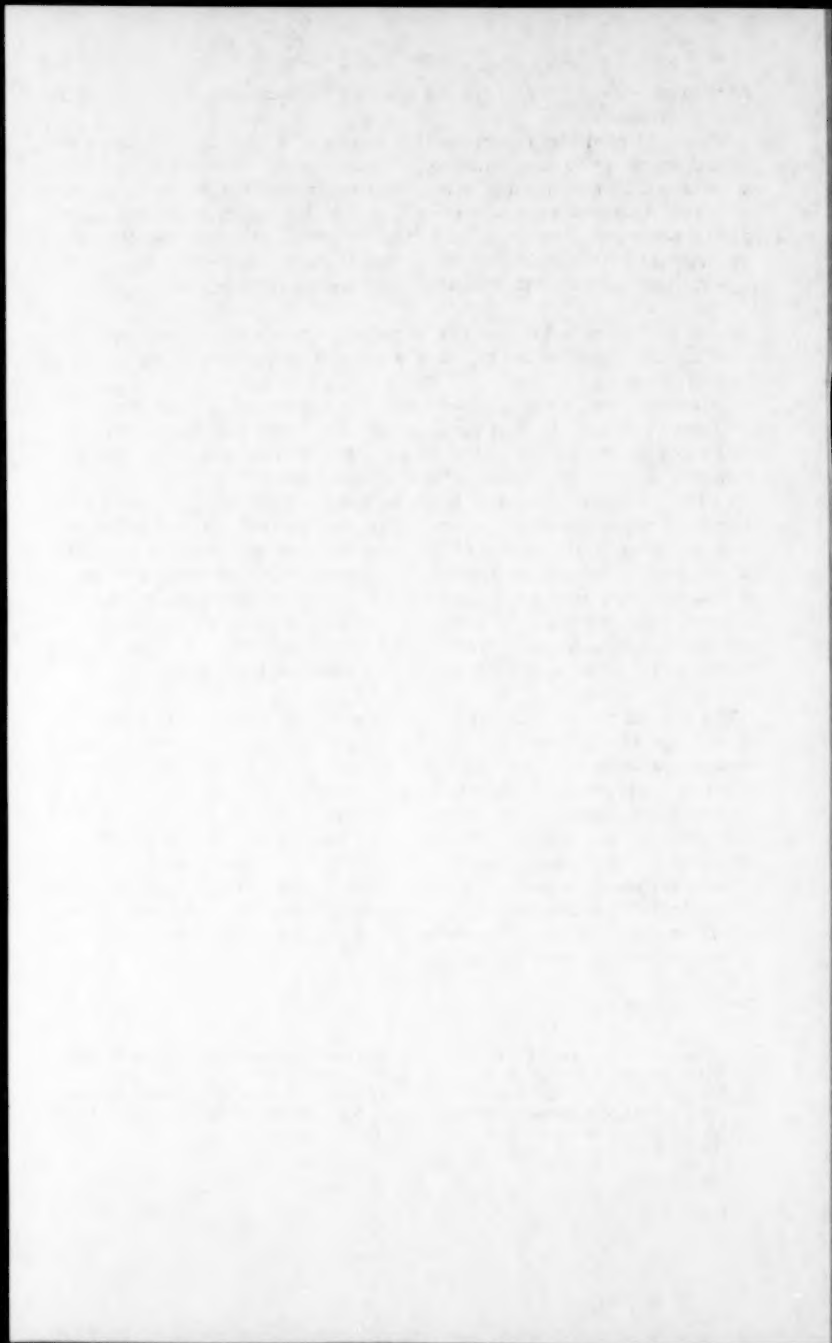
2. In urbanizing areas, the preventive approach to requiring removal of particulate pollution, by dual purpose detention basins built by developers, is institutionally feasible (26). This does not add greatly to costs of providing detention basins in the interest of flood control only.

3. The most feasible approach to improving water quality in small fully-developed urban streams is a local program of surveillance and monitoring. In such a program, the pollution from minor industrial and commercial facilities is identified, and firms are required to institute proper methods of disposing of both liquid and solid wastes. If cooperation is not obtained, the full sanction of an NPDES permit can be imposed. The next attention should be given to minimizing combined sewer and sanitary sewer overflows. Any question of treating urban runoff as a whole should be a matter of lesser priority.

The real urgency of obtaining a consensus on such matters is that the EPA, through the Clean Water Act, has the legal power to impose water quality standards upon every "pipe, ditch or channel" carrying polluting substances. Recently, there are some signs that these powers may be invoked. As stated by the author, local officials are apprehensive about arbitrary imposition of such controls, and rightfully so. The policy on this matter will probably be set within the next year or so; and many billions of dollars could be wasted if decisions are unrealistic. The writer much doubts that the full scientific knowledge of all of the aspects of urban runoff will be obtained early enough to influence the outcome. It is essential that a fuller understanding be arrived at of the significance of what we already know.

#### APPENDIX.—REFERENCES

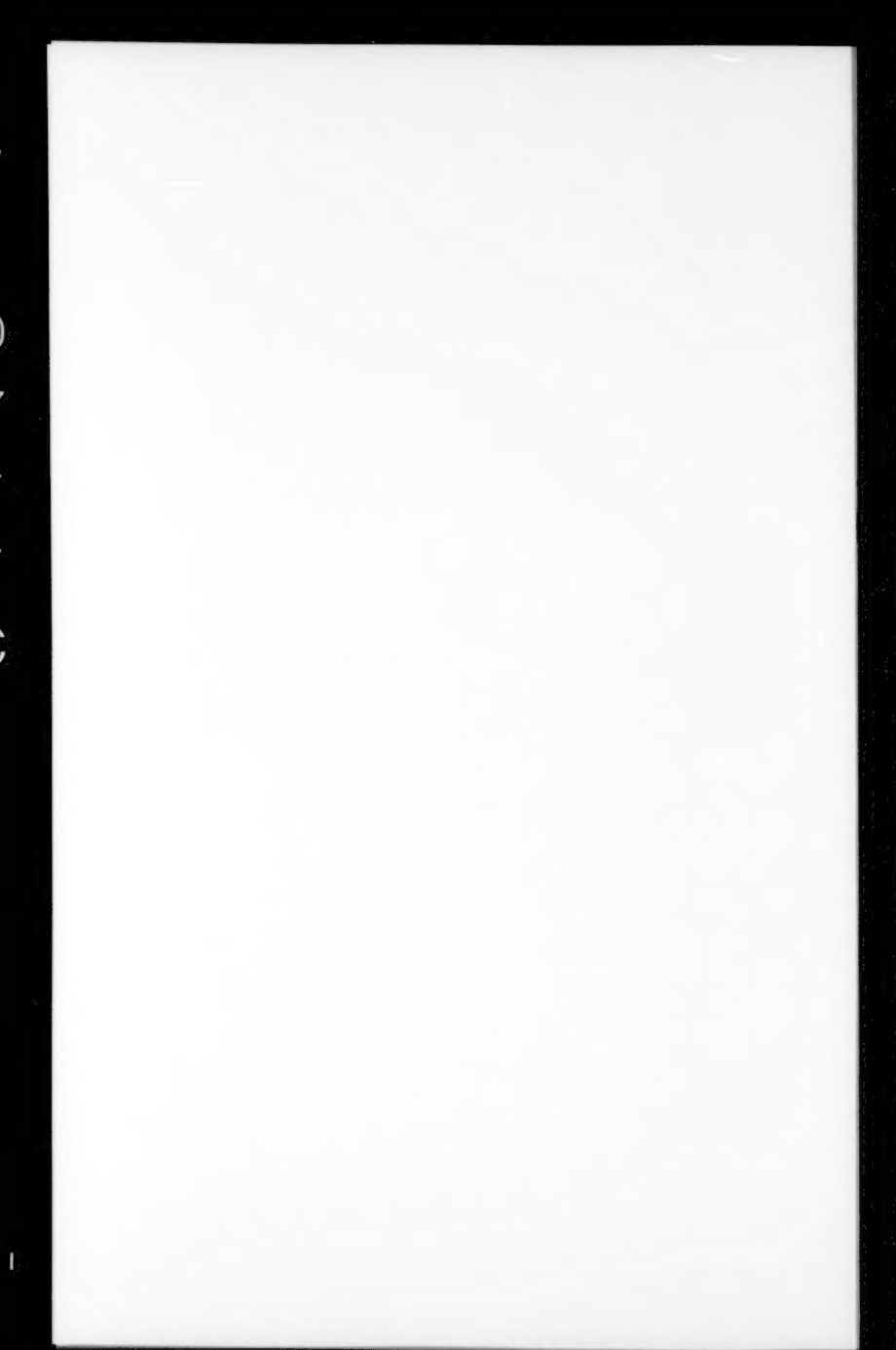
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26. Whipple, W., Jr., "Dual-Purpose Detention Basins," *Journal of the Water Resources Planning and Management Division*, ASCE, Vol. 105, No. WR2, Proc. Paper 14860, Sept., 1979, pp. 403-412.



1. The first part of the document is a list of names and addresses of the members of the committee. The names are written in a cursive hand, and the addresses are written in a printed hand. The list is organized in two columns, with the names in the left column and the addresses in the right column. The names are: John A. Smith, John B. Smith, John C. Smith, John D. Smith, John E. Smith, John F. Smith, John G. Smith, John H. Smith, John I. Smith, John J. Smith, John K. Smith, John L. Smith, John M. Smith, John N. Smith, John O. Smith, John P. Smith, John Q. Smith, John R. Smith, John S. Smith, John T. Smith, John U. Smith, John V. Smith, John W. Smith, John X. Smith, John Y. Smith, John Z. Smith. The addresses are: 123 Main St., 456 Main St., 789 Main St., 101 Main St., 202 Main St., 303 Main St., 404 Main St., 505 Main St., 606 Main St., 707 Main St., 808 Main St., 909 Main St., 1010 Main St., 1111 Main St., 1212 Main St., 1313 Main St., 1414 Main St., 1515 Main St., 1616 Main St., 1717 Main St., 1818 Main St., 1919 Main St., 2020 Main St., 2121 Main St., 2222 Main St., 2323 Main St., 2424 Main St., 2525 Main St., 2626 Main St., 2727 Main St., 2828 Main St., 2929 Main St., 3030 Main St., 3131 Main St., 3232 Main St., 3333 Main St., 3434 Main St., 3535 Main St., 3636 Main St., 3737 Main St., 3838 Main St., 3939 Main St., 4040 Main St., 4141 Main St., 4242 Main St., 4343 Main St., 4444 Main St., 4545 Main St., 4646 Main St., 4747 Main St., 4848 Main St., 4949 Main St., 5050 Main St., 5151 Main St., 5252 Main St., 5353 Main St., 5454 Main St., 5555 Main St., 5656 Main St., 5757 Main St., 5858 Main St., 5959 Main St., 6060 Main St., 6161 Main St., 6262 Main St., 6363 Main St., 6464 Main St., 6565 Main St., 6666 Main St., 6767 Main St., 6868 Main St., 6969 Main St., 7070 Main St., 7171 Main St., 7272 Main St., 7373 Main St., 7474 Main St., 7575 Main St., 7676 Main St., 7777 Main St., 7878 Main St., 7979 Main St., 8080 Main St., 8181 Main St., 8282 Main St., 8383 Main St., 8484 Main St., 8585 Main St., 8686 Main St., 8787 Main St., 8888 Main St., 8989 Main St., 9090 Main St., 9191 Main St., 9292 Main St., 9393 Main St., 9494 Main St., 9595 Main St., 9696 Main St., 9797 Main St., 9898 Main St., 9999 Main St.







1. The first part of the paper discusses the importance of the study of the history of the United States. It is argued that a knowledge of the past is essential for a full understanding of the present and for the development of a sound policy for the future. The author points out that the study of history is not only a means of acquiring knowledge, but also a means of developing the ability to think critically and to make sound judgments.

2. The second part of the paper discusses the importance of the study of the history of the United States. It is argued that a knowledge of the past is essential for a full understanding of the present and for the development of a sound policy for the future. The author points out that the study of history is not only a means of acquiring knowledge, but also a means of developing the ability to think critically and to make sound judgments.

3. The third part of the paper discusses the importance of the study of the history of the United States. It is argued that a knowledge of the past is essential for a full understanding of the present and for the development of a sound policy for the future. The author points out that the study of history is not only a means of acquiring knowledge, but also a means of developing the ability to think critically and to make sound judgments.

4. The fourth part of the paper discusses the importance of the study of the history of the United States. It is argued that a knowledge of the past is essential for a full understanding of the present and for the development of a sound policy for the future. The author points out that the study of history is not only a means of acquiring knowledge, but also a means of developing the ability to think critically and to make sound judgments.

5. The fifth part of the paper discusses the importance of the study of the history of the United States. It is argued that a knowledge of the past is essential for a full understanding of the present and for the development of a sound policy for the future. The author points out that the study of history is not only a means of acquiring knowledge, but also a means of developing the ability to think critically and to make sound judgments.

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1. Titles must have a length not exceeding 50 characters and spaces.
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5. All mathematics must be typewritten and special symbols must be identified properly. The letter symbols used should be defined where they first appear, in figures, tables, or text, and arranged alphabetically in an appendix at the end of the paper titled Appendix.—Notation.
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12. A set of conclusions must end the paper.
13. Dual units, i.e., U.S. Customary followed by SI (International System) units in parentheses, should be used throughout the paper.
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